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(FINAL REPORT)

FURTHER EXPERIMENTS ON THE RANGE OF VISUAL SEARCH

TECHNICAL DOCUMENTARY REPORT NO. ESD-TDR-65-169

JANUARY 1965

John Volkmann
Horace H. Corbin

DECISION SCIENCES LABORATORY
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

ESRH

Project 7682, Task 768204

(Prepared under Contract No. AF 19 (628)-2443 by Mt. Holyoke College, South Hadley, Massachusetts.)

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ABSTRACT

This report describes six experiments on visual search, in continuation of those described in the report ESD-TDR-64-535, entitled The Range of Visual Search. Two essential terms in the report are critical number and basal time, defined by the following operations. Median latency of search is plotted as a function of the number of elements in the matrix, for each subject and experimental condition. At low numbers of elements the latency is nearly constant; this is the basal time. Then there occurs a transition to longer latencies. The critical number is the number of elements at which the transition occurs.

The aim of the first experiment was to discover whether the critical number varies with the density of the stimulus matrix. It certainly does, over the entire range of densities employed. Nevertheless, the area corresponding to the critical number is apparently constant over a range of low densities. (This is the area of fast search.) Over a range of high densities, this area decreases considerably. Basal time does not vary with density.

The second experiment aimed to check the first one, and to provide evidence on the shape of the area of fast search. The analysis was in terms of the location of the critical elements in the matrix. The constancy of area at low densities was confirmed, although the check was very insensitive. Basal time is indeed constant. The shape of the area appears to be as previously described: ovaloid, with the longer axis horizontal.

The third experiment aimed to try out a more economical method for mapping out the area of fast search. It used a single line of elements, tilted at various angles. The method is promising, although further work on it is required. There is evidence for patterns of successive search that are characteristic of individual human subjects.

The fourth experiment used the method of brief exposures, specially developed apparatus, and a different discrimination (the tilt of line-segments about the vertical). The preceding report had described the expansion of the area of fast search with increasing exposure time, and had related this expansion to the Roscoe-Bunsen Law. The results confirm this interpretation, although the number of observations is very small.

The fifth and sixth experiments dealt with the subdivision of matrices. Does subdividing speed up successive search? One cannot yet conclude that it does; if subdivisions are used, it will presumably be to ensure the reliability of search, at some expense of speed. The method of subdividing is important. There is evidence that speed of successive search is maximal when the number of elements in each cell of the matrix is about equal to the critical number.

The report makes specific suggestions about improved methods for studying both fast search and successive search.

PUBLICATION REVIEW AND APPROVAL

This Technical Documentary Report has been reviewed and is approved.

Donald W Connolly
DONALD W. CONNOLLY
Chief, Display Division
Decision Sciences Laboratory

for James S. Duva
ROY MORGAN
Colonel, USAF
Director, Decision Sciences Laboratory

Foreword

The subject-matter of this contract was the effect of subdividing a stimulus matrix on the speed of visual search within that matrix. Two experiments dealt with this problem; they come last in the report. More important, in the light of the results, is that the contract enabled PRU to continue with its experiments on the range of visual search. Four of these experiments are reported here, in varying amounts of detail. Because the research is a continuation of some reported earlier (in the Range of Visual Search, ESD-TDR-64-535), the reader is advised to orient himself with the aid of that report.

Apart from the results, some of which should be interesting to those concerned, the most impressive thing about this project was its economy. The Air Force is receiving a lot for a little. This is partly because existing apparatus and techniques could be used over again; mainly because of the services of six able undergraduate students who worked for the most part without pay. Even the Peace Corps would find it hard to match that record. The students were the Misses Margaret Philbrick (Mrs. David Truman), Nancy Johanson, Dorothy McKane, Joy Halfter, Patricia Napper, and Kathryn Eppston.

Credit is due to Mr. Gary Davis and Mr. Max Kotfila for the photographs.

This report has been written largely by the undersigned, as Director of PRU. Dr. Corbin has been active in the experiments throughout. E.P. Reese (Mrs. T.W. Reese) has been most helpful with problems of illustration. Dr. T.W. Reese has cooperated as chairman of the Department of Psychology and Education.

Once again we acknowledge the patience and helpfulness of officials of the Air Force: Mr. William H. Sumby, the project monitor; Mr. C.W. Cantrell, the contract officer; Mr. Bennett Bolton and Mr. Gaetan J. Gagnier, the property representatives.

The business office and maintenance division of Mount Holyoke College have supported our efforts, as always. The officers include: Mr. Otto Kohler, Business Manager; Mr. Edward Babbitt, Comptroller; Mr. Lawrence Remillard, Assistant to the Comptroller; Mr. Earl Frank, Assistant Superintendent in Charge of Operations.

John Volkmann
Director

Table of Contents

I. Introduction

This report is a direct continuation of another one, and the questions that it considers are mainly those that grow out of the preceding report.[1] The best introduction is therefore to quote in full the abstract of the preceding report:

"THE RANGE OF VISUAL SEARCH -(Abstract): The aim of these experiments was to study the process of visual search in its early phases. Individual human subjects searched in a projected matrix of elements for one element unlike the rest; e.g., for a triangle in a matrix otherwise composed of circles. In the method of lasting exposure, the matrix was exposed until the subject responded, and the dependent variable was the latency of the response. In the method of brief exposure, the exposure time was limited, and the dependent variables were the percentage of positive responses and the latency of the positive responses. ("Positive response" means that the subject found the desired element). Among the independent variables (or classes of them) in various experiments were the following: the total number of elements in the matrix; the type of discrimination (form, area, color); the external form and internal pattern of the stimulus array. In analyzing the results of a typical experiment, the median latency is plotted as a function of the number of elements in the stimulus array.

"The graph begins at nearly zero slope, and usually shows a small discontinuity or a sigmoid transition leading to slightly higher latencies. This transition locates the critical number (CN): the number of elements at which it occurs. The critical number varies considerably with the type of discrimination required, and with the stimulus difference between the critical and background elements. It can be determined for arrays that are irregular in external contour or internal pattern.

"The critical number represents some discriminatory limit or limits; it may be a limit of area rather than of number. In dealing with large matrices, the subject apparently searches rapidly in a region around the fixation point (the initial sub-matrix). By definition, this has an area equal to that covered by the critical number in the matrix. The interpretation of the critical number and the initial sub-matrix is partly in terms of saccadic eye movements, though none have been photographed as yet.

"The region of fast search may have at least an approximate shape. One experiment, using the method of brief exposures, indicated the shape to be ovaloid, with most of its area lying above the fixation point."

The present report deals with five questions, and elaborations of them:

1. Is the critical number (CN) a limit that is most usefully regarded

as a limit of number of elements, or as a limit of the stimulus area covered by the critical number? As the preceding report pointed out (p.88), the question can be examined experimentally by varying the stimulus-density (the number of elements per unit area). The first two experiments in the present report varied stimulus density, and gave a positive answer to a more specific question: are there conditions under which the CN, or the area covered by it, is independent of density?

2. Does the region of fast search have a definite shape; if so, what is it? The second, third, and fourth experiments shed some light on this longstanding and principal question.

3. Can one develop a relatively economical method for studying the region of fast search? The third experiment represents some progress in this direction.

4. Under what conditions does the region of fast search expand with increasing exposure-time? The study of Chaikin et al showed an expansion under their conditions. The fourth experiment, with special apparatus and technique, suggests an answer to this question, although the number of observations is very small.

5. What is the effect on the speed of visual search of subdividing the matrix that is being searched? This question does not grow directly out of the preceding experiments; it is raised by the practical difficulties of searching large areas for low probability targets. The last two experiments shed some light on it.

II. A constant-area function for visual search

The preceding introduction raised two closely related questions: is the critical number (CN) a limit that is most usefully regarded as a limit of <u>number</u> of elements, or as a limit of the stimulus <u>area</u> covered by the critical number? The question is to be answered by varying the surface-density of the stimuli. The second question is: are there conditions under which the CN, or the area covered by it, is independent of stimulus density? A measurable limit of any kind may be worth determining, because the process of human search is so important. Nevertheless, a limit that is invariant when some principal parameters vary is of especial interest. The invariance may some day provide a clue to the search process. Stevens has argued for the importance of functional invariances in general.[2]

The preceding report considered these questions briefly, and referred to an experiment conducted by Miss Burke and Miss Smith. These students used square matrices and varied their density. Because the number of perfect squares is too small, within the useful range of number-of-elements, there turned out to be too few points on the graphs; no stable conclusions could be drawn about invariance. It was subsequently discovered that the critical number (CN) could be determined for various external matrix-shapes, rather different from squares. As a result, the present experiment used rectangular matrices of approximately a 2:1 ratio, width to height. Relatively small increases in number of-elements could be obtained by adding another row of elements to the height, or another column to the width. Miss Johanson and Miss McKane conducted the experiment and fought through its complications to a susccessful conclusion.

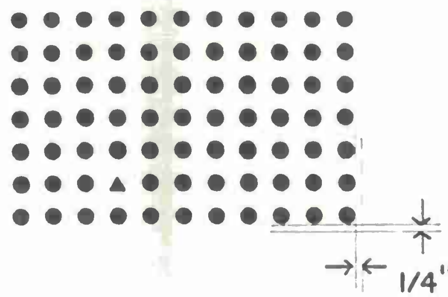
Next we should consider the definitions of some stimulus-variables. The number of elements in the matrix offers no difficulty; except for the "blank" stimuli, one of the elements in the matrix is an equilateral triangle resting on a base; the other elements are solid black circles of about the same apparent area as the triangle. The area covered by the matrix is not so simple. Most probably it should not be limited by lines that are drawn between the outside elements center-to-center. The most appropriate stimulus-variable would seem to be one that corresponds most closely to the apparent area of the matrix. Consequently we have delimited the area by means of a line that lies outside the outermost elements and that includes a narrow white band outside them. (see Fig. 1). The white band is of constant width throughout the entire range of stimulus areas and densities; its dimensions on the projection screen appear in the figure. The density of the matrix is then to be defined as a surface density, the number of elements per unit area on the projection screen.

The technique for varying density is explained in the preceding report, Appendix A. A printed plastic master sheet contains a large matrix of solid black circles at the maximum density. The master is mounted on a transparent plastic backing. External rows and columns of circles can then be stripped off to determine the area of a stimulus matrix; internal rows and columns can be stripped off to reach the desired lesser density. Fig. 1 shows a sample matrix with a relatively small area and the maximum density; also a sample with a relatively large area and the minimum density. These matrices, like all of the others, are rectangular with a width-to-height ratio of approximately 2:1.

All three of the stimulus parameters, number-of-elements, area, and density varied in this experiment. Table I lists each of the stimuli, specified in each of the three parameters; also stated is the number of elements in the rows and the columns of each stimulus pattern. The densities in each sixth of the table vary slightly because of the inclusion in the area of the narrow band outside the outermost elements. Apart from this consideration, each sixth of the table represents a stimulus density.

Fig. 1

Showing two examples of stimulus matrices used in this experiment. At the top, a matrix of the maximum density, containing 77 elements. At the bottom (and turned on its side), a matrix of the minimum density containing 20 elements (no triangle). The dimension indicates the width in inches, as projected, of the narrow white band that is included in the measure of stimulus area. The band has the same width for all matrices.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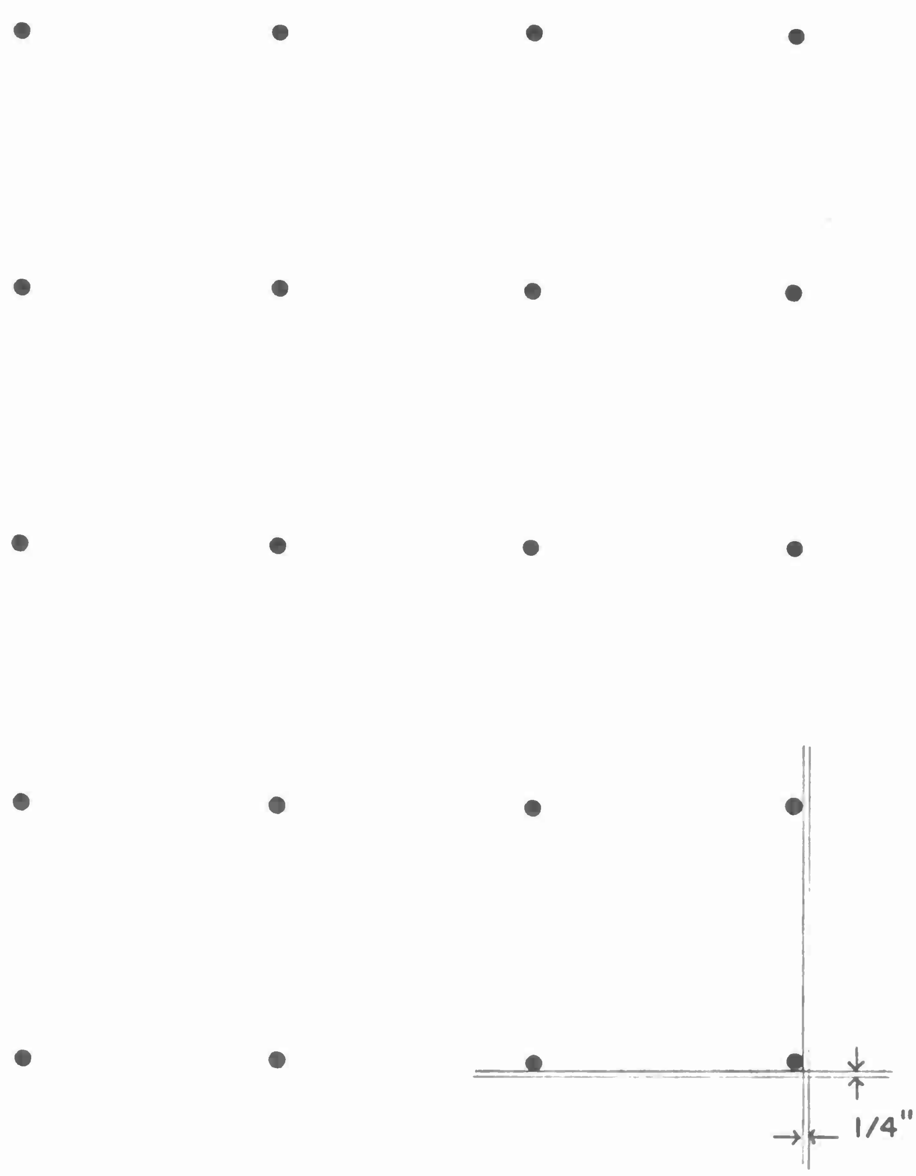
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Table I

Listing for each of six stimulus density-ranges the proportion of each matrix in no. of elements; the total no. of elements in the matrix; the area of the matrix in sq. in. as projected; the density of the particular matrix, as computed from the total no and the area; the corresponding median latencies in secs. for each of the five subjects. Each median is computed from 48 observations for all matrices containing 21 or more elements; for smaller matrices, the N varied.

Table I

Density 0.890

Matrix	No. of elements	Area	Density	Mdn. latencies AH	EW	NCo	NCa	SM
57x33	1881	2113.5	.890	3.09	3.58	3.56	6.09	3.66
49x25	1225	1381.6	.890	2.40	3.35	2.93	3.01	2.28
41x21	861	971.1	.890	2.14	3.04	2.69	2.58	2.33
37x17	629	709.4	.890	1.44	2.34	1.40	2.05	1.72
25x15	375	422.9	.890	1.31	1.85	1.35	1.50	1.85
21x12	252	284.2	.890	.88	1.27	1.01	1.10	1.05
21x11	231	260.5	.890	.80	1.12	.78	1.09	.96
18x10	180	203.0	.890	.74	1.11	.72	.94	1.08
17x9	153	172.6	.890	.66	1.15	.83	1.08	.94
19x7	133	150.0	.890	.73	.98	.75	.85	.95
14x8	112	126.3	.890	.52	.83	.63	.71	.81
14x7	98	110.5	.890	.59	.87	.66	.74	.86
12x7	84	94.7	.890	.52	.85	.55	.74	.81
12x6	72	81.2	.890	.53	.78	.61	.71	.87
10x6	60	67.7	.890	.55	.74	.53	.60	.84
9x5	45	50.8	.890	.50	.62	.53	.60	.76
8x4	32	36.1	.890	.50	.63	.52	.60	.72
7x3	21	23.7	.890	.50	.59	.50	.54	.71

Densities 0.224-0.319

Matrix	No. of elements	Area	Density	Mdn. latencies AH	EW	NCo	NCa	SM
29x17	493	2205.4	.224	1.84	3.44	2.57	3.11	1.99
25x13	325	1428.8	.227	1.74	1.85	1.86	2.26	1.77
21x12	252	1096.3	.230	1.44	2.09	1.37	1.86	1.81
19x11	209	882.9	.237	1.52	2.29	1.54	1.67	1.63
19x9	171	725.9	.236	1.01	1.18	1.04	1.67	1.09
17x8	136	568.6	.239	.92	1.30	.77	1.29	1.01
14x8	112	463.9	.241	.82	1.15	.86	1.15	1.11
13x7	91	370.2	.246	.62	.91	.71	.89	.90
11x7	77	310.0	.248	.58	.83	.69	.82	.86
11x6	66	260.8	.253	.60	.93	.79	.89	.88
9x6	54	210.1	.257	.51	.79	.62	.76	.82
9x5	45	170.4	.264	.51	.79	.59	.68	.83
9x4	36	130.7	.275	.49	.70	.55	.64	.75
6x4	24	83.5	.288	.48	.65	.51	.58	.70
5x3	15	47.2	.319	.47	.57	.48	.55	.67

Table I, cont'd

Densities 0.104-0.148

Matrix	No. of elements	Area	Density	Mdn. latencies AH	EW	NCo	NCa	SM
19x11	209	2002.0	.104	2.22	3.51	2.61	3.09	2.52
19x9	171	1550.1	.110	1.14	3.07	1.54	1.57	1.59
17x9	153	1403.0	.109	1.16	1.73	1.17	1.76	1.25
19x7	133	1216.7	.109	1.42	1.72	1.26	2.00	1.42
17x7	119	1101.3	.108	1.08	1.51	1.36	1.88	1.13
15x7	105	965.3	.108	1.08	1.44	1.37	1.46	1.13
13x7	91	829.3	.109	1.00	1.31	1.19	1.38	1.19
12x7	84	761.3	.110	.90	1.03	.92	1.05	1.06
12x6	72	601.4	.119	1.02	1.07	1.20	1.27	1.06
10x6	60	524.5	.114	.68	1.05	.82	1.20	1.01
10x5	50	423.6	.118	.68	1.04	.75	.92	.84
8x5	40	331.5	.120	.53	.77	.65	.70	.82
8x4	32	252.5	.126	.50	.75	.62	.69	.75
6x4	24	182.4	.131	.50	.67	.52	.60	.73
5x3	15	101.2	.148	.47	.60	.50	.56	.72

Densities 0.062-0.095

Matrix	No. of elements	Area	Density	Mdn. latencies AH	EW	NCo	NCa	SM
15x9	135	2145.1	.062	1.59	1.93	2.05	3.15	2.13
15x8	120	1882.0	.063	1.32	1.54	1.41	2.64	1.40
15x7	105	1618.8	.064	.96	1.40	1.10	1.60	1.08
13x7	91	1390.1	.065	1.27	1.67	1.48	2.23	1.41
11x7	77	1161.3	.066	.95	1.17	1.08	1.61	1.18
10x6	60	876.7	.068	.58	.87	.66	.87	.93
9x5	45	629.4	.071	.74	1.03	.68	.98	.96
8x4	32	419.2	.076	.66	.95	.79	1.06	.94
6x4	24	302.0	.079	.51	.74	.56	.73	.84
5x3	15	166.1	.09	.50	.71	.54	.63	.74
4x3	12	126.1	.095	.47	.63	.50	.54	.73

Table I, cont'd

Densities 0.030-0.060

Matrix	No. of elements	Area	Density	Mdn. latencies AH	EW	NCo	NCa	SM
10x6	60	1998.9	.030	1.05	1.38	1.64	1.89	1.42
9x6	54	1778.8	.030	.86	1.54	1.26	1.98	1.28
10x5	50	1606.5	.031	1.33	1.19	.93	1.46	1.02
9x5	45	1430.0	.031	.86	1.05	1.13	1.51	1.17
8x5	40	1253.5	.031	.87	1.21	.87	1.63	1.05
9x4	36	1081.2	.033	.87	1.25	.96	1.25	1.09
8x4	32	947.7	.033	.78	.98	.84	1.37	1.14
6x4	24	680.8	.035	.66	.87	.63	.99	.86
6x3	18	461.2	.039	.54	.76	.66	.91	.86
4x3	12	280.3	.042	.51	.77	.55	.72	.76
3x2	6	99.5	.060	.47	.56	.50	.53	.72

Densities 0.018-0.035

Matrix	No. of elements	Area	Density	Mdn. latencies AH	EW	NCo	NCa	SM
8x5	40	2208.3	.018	1.04	1.44	1.26	1.72	1.34
7x5	35	1896.2	.018	1.20	1.37	1.30	1.84	1.27
8x4	32	1666.4	.019	.98	1.35	1.33	1.50	1.26
7x4	28	1430.9	.019	.71	.89	.88	1.22	.98
6x4	24	1195.3	.020	.71	1.03	.77	1.07	.96
7x3	21	965.5	.021	.64	.98	.90	1.52	.99
6x3	18	806.6	.022	.70	1.05	.84	1.09	.99
5x3	15	647.7	.023	.61	.88	.65	.97	.84
4x3	12	488.7	.024	.58	.77	.63	.84	.84
3x2	6	170.8	.035	.47	.62	.50	.55	.69

Next to describe the locations in the matrices of the critical element the triangle. For all matrices of 7 x 3 elements and fewer, this triangle appeared in every possible position. For all matrices with more elements, there were 16 locations scattered over the area of the matrix. When the number of elements in both the rows and the columns was odd, one stimulus position was the exact center of the matrix. Latencies for this position helped to check the basal time and the CN, as explained below. Blank stimuli (i.e., matrices containing no triangle) were prepared for each matrix of n x n' elements, to provide a further check on the validity of S's responses, and to maintain the conditions of uncertainty. The blank stimuli occurred at random along with the remaining stimuli, on the average one out of 17 times. If S found no triangle she did not respond manually, but said "blank" to E.

To describe the order of the stimuli: randomization was complete over all the stimulus variations. Consequently the S knew that the next stimulus would be rectangular in external shape, with the longer axis horizontal, and that it would be centered about the fixation point. She did not know what the number of elements, area or density would be; or where in the matrix the triangle would be, or even if there would be a triangle at all. Our experiments have furnished repeated indications that these conditions of uncertainty are important.

There were five S's, all female undergraduate students at Mount Holyoke. All met the most demanding set of standards of the Bausch and Lomb Modified Orthorater, and none wore glasses.

There were 80 different matrices and approximately 16 different locations of the critical element in each; hence there were about 480 stimulus sheets. Each S saw the projection of each sheet three times over the course of the experiment. This yielded a total N per S of 3864, and a total N for the experiment of 19,320. The observations occupied about 16 hours with each S.

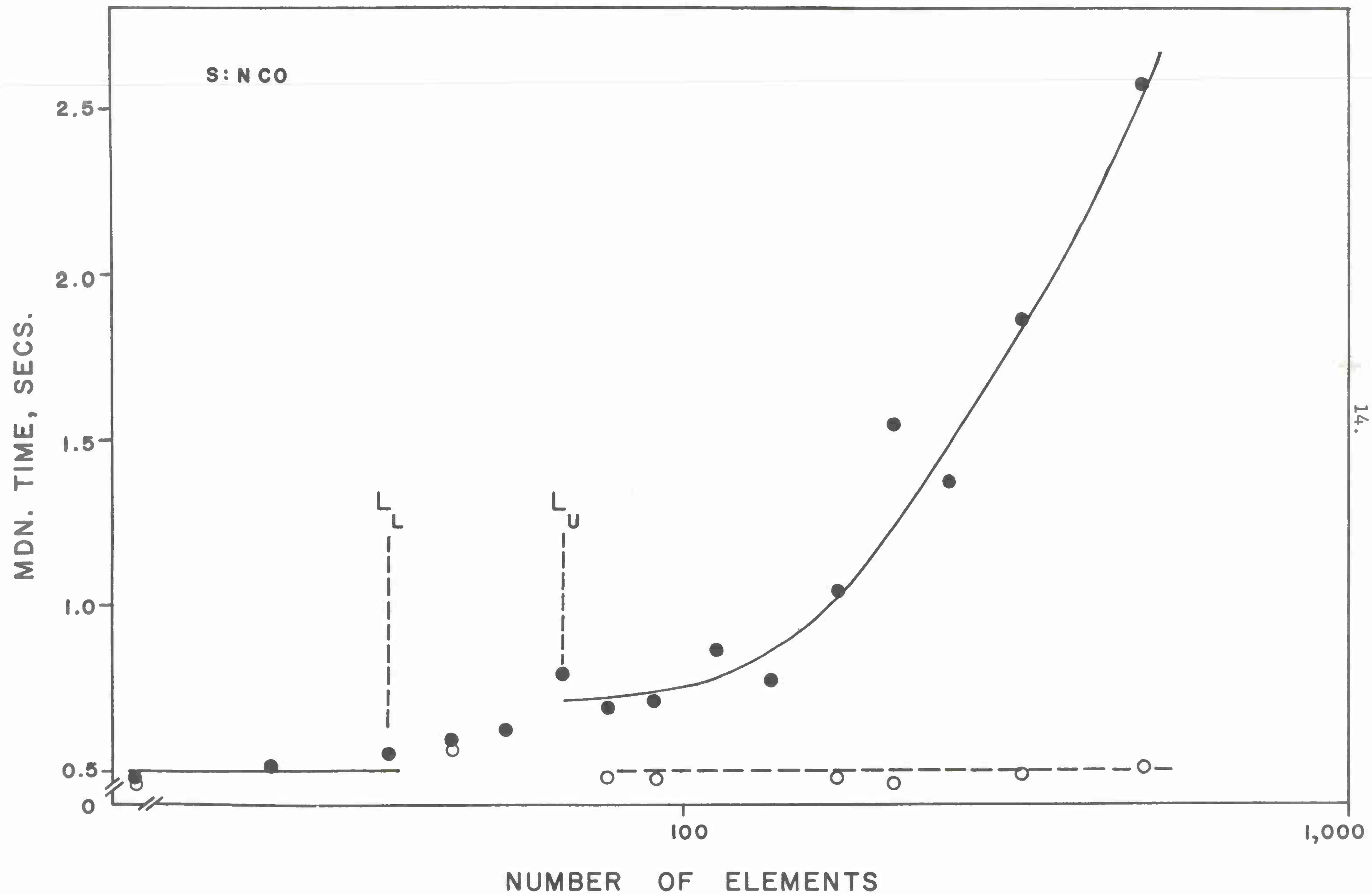
The apparatus and experimental situation were the same as those described in the preceding report (the improved method, pp. 18-25), and are given here only very briefly. The stimulus material was prepared as black on white, on 11" x 11" sheets; it was shown with a large opaque projector. The S fixated a small cross in the middle of a large screen placed 9.5 ft. from her eyes. A special shutter exposed the matrix, centered about the fixation mark, and the timing of response-latency began. S searched under an instruction for speed. If and when she saw the triangle, she snapped her right index finger forward, out of a V-shaped notch. Simultaneously, the response latency was terminated and recorded; the matrix field went off, and a small spot-projector, mounted on the S's finger, went on; an erasing field covered the projection screen. S pointed to the place where the triangle appeared, and E checked the approximate accuracy of the pointing. The instructions determined S's uncertainties as listed above, and the actual, randomized sequence of stimuli was in accord with them.

Table I contains the median latencies for each S and each stimulus condition. Each median is based on an N of about 48, which reflects the 16 different target locations for most matrices and 3 showings of each. The most important dependent variables in the experiment are the critical number (CN) and the basal response time. Fig. 2 illustrates the determination of the CN. Median latency was plotted as a function of the number of elements in the matrix, for each combination of S and approximate density. At low numbers the latency is nearly constant; this is the basal time. Then the graph shows a transition to slightly higher latencies. The CN is determined by inspection as a pair of limits: the highest stimulus number of elements

Fig. 2

Showing for one subject and one density an example of the determination of the lower limit L_L and the upper limit L_U of the critical number. Median latency for all locations of the critical element is plotted as a function of the no. of elements in the matrix, on semi-logarithamic axes (solid circles). The open circles represent the median latencies for a central location, (i.e., at the fixation point).

Fig. 2



S:NCO
MDN. TIME, SECS.
2.5
2.0
1.5
1.0
0.5
0
L_L
L_U
100
1,000
NUMBER OF ELEMENTS

below the transition, and the lowest stimulus number above it. Of the 30 possible transitions in the experiment, 27 could be made out in this way with varying amounts of confidence. The resulting CN limits appear in Table II.

A glance at the table will answer one of the principal questions in our research. The CN is not invariant with density; it is not to be most usefully regarded as a limit of the number of elements. Fig. 3 shows the variation for one of the S's, AH. The measures are plotted as vertical line-segments connecting the upper and lower CN limits. Because of our particular definitions of area and density, the upper and lower limits are plotted at two different densities, and the vertical line is plotted at a density intermediate between the two. The graph continues to rise over the whole range of densities, although (as we shall see) the area covered by the CN is decreasing at the higher densities. Apparently more elements are being processed in the fast search, even though the total area that they cover is less. The functional relation that Fig. 3 deals with may turn out to be more complicated than the smooth curve suggests.

Now to the principal finding of this experiment: Figs. 4-7 inclusive show the <u>area</u> of the stimulus matrices at the CN limits, as a function of the stimulus density at those limits. The graphs have some obvious limitations, but they show the same general relation for four of the S's. Search area is constant over a region of lower densities. Over this region, the limit of search is better stated as a limit of area rather than as a limit of the number of elements. With changing density, the initial number of elements has changed in such a way as to reflect an invariant area. Over a region of higher densities, search area decreases, although the shape of the curve is not clear.

The relation dealt with in Figs. 4-7 is limited naturally at both ends.

Table II

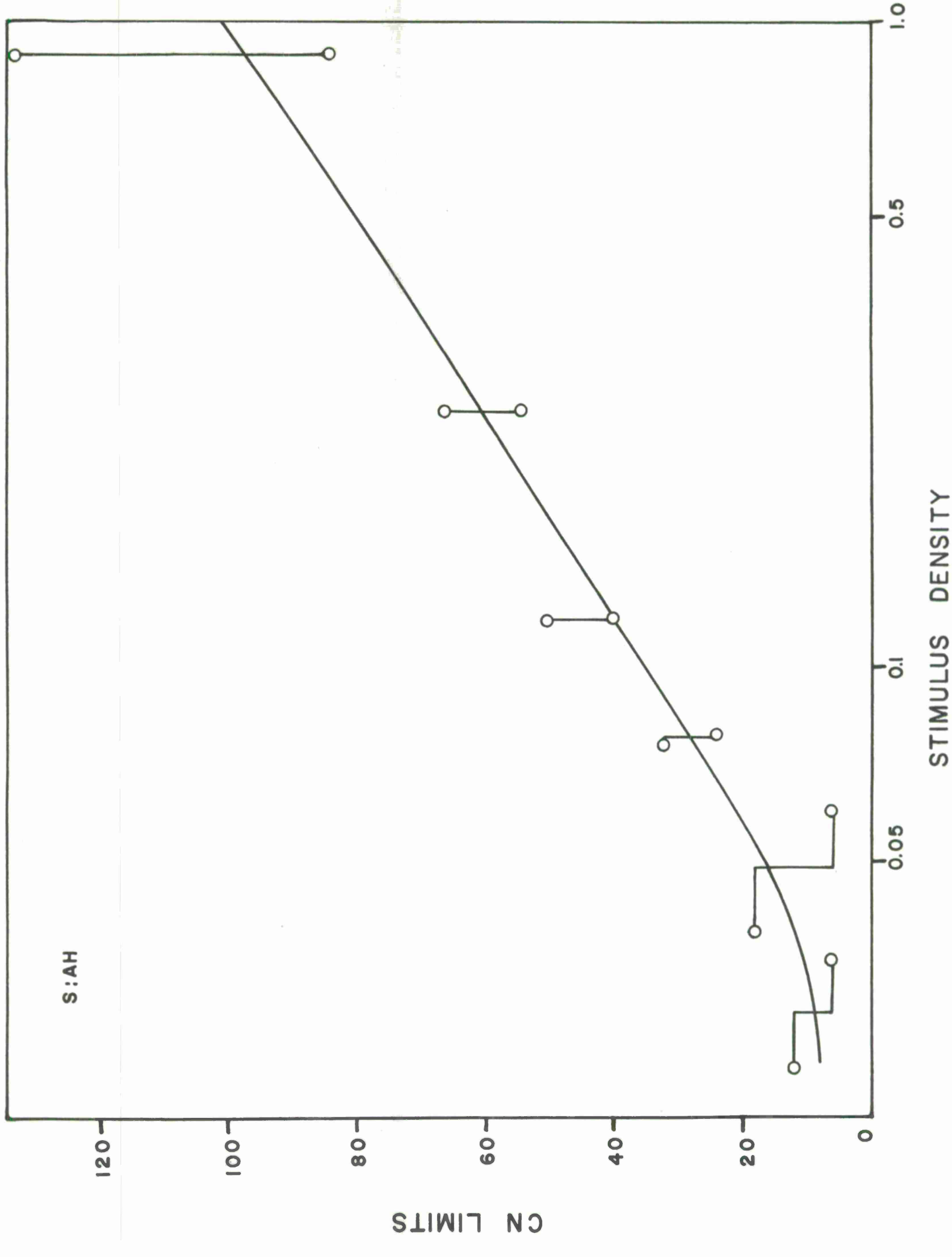
Limits of the critical number (CN) for all S's and ranges of stimulus density. The tabular entries represent the highest stimulus number of elements below the transition in the graph relating latency to number of elements; also the lowest stimulus number of elements above the transition. Refer to Fig. 2 for an example.

	CN limits, for S's:				
Density	AH	EW	NCo	NCa	M
0.890	84-133	45-60	60-72	60-72	32-60
0.224-0.319	54-66	15-24	36-66	36-66	24-45
0.104-0.148	40-50	-----	24-32	24-32	24-40
0.062-0.095	24-32	-----	24-32	15-24	15-32
0.030-0.060	6-18	6-12	6-18	6-12	6-18
0.018-0.035	6-12	-----	6-12	6-12	6-12

Fig. 3

Showing for one subject (AH) the wide variation of the limits of the critical number, as a function of stimulus density. The axes are semilogarithmic. The two limits corresponding to a systematic variation of the no. of elements are plotted at different densities, because the computed densities for different stimulus areas are not the same.

Fig. 3


S:AH
STIMULUS DENSITY
CN LIMITS
0
20
40
60
80
100
120
0.05
0.1
0.5
1.0

At a somewhat higher density than the highest one used here, the elements of the matrix will overlap spatially and discrimination will become impossible. At very low densities the CN becomes indeterminate for two reasons. First, the critical elements will seldom be found within the initial area of fast search; there are few elements of any kind, critical or background, within this area. There will be no basal time and no transition. Secondly, there are too few stimulus values available to determine the CN limits; the points in the plots corresponding to Fig. 2 are too far apart. The second difficulty appears already in the wide separations of the CN limits at low densities in Figs. 4-7.

If another experiment is to be done that follows the pattern of this one, it might use matrices of a roughly oval-shape, so that a few elements can be added at a time to give more points on the plot. A new experiment might also begin with a slightly higher maximum density; this would provide one or two more points on the plots corresponding to Figs. 4-7. The experiment might also employ a different discriminable characteristic to compare with the form-discrimination measured here.

The four S's yielded somewhat different invariant areas, as read from the horizontal lines drawn in Figs. 4-7. The lowest is 220 sq. in. for S: NCa; the highest is 377 sq. in. for S:AH. The mean of the four is about 305 sq. in. This corresponds to a circle of 19 3/4" diameter, or a square of 17 1/2" on a side. The diameter of the circle subtends a visual angle of about 10^{o}. The S's also differed in the value of density that separates the two regions of the graphs in Figs. 4-7. The graph for the fifth S, EW, could not be drawn at all because her data yielded too few determinable values of the CN limits.

The finding of an area of fast search that is invariant with density may turn out to be important. In this density-independent region only the area

Fig. 4

Showing for subject AH the stimulus area that is covered by the CN limits, as a function of stimulus density. The axes are semi-logarithmic. In this and the succeeding three graphs, area appears to be constant over a range of low densities.

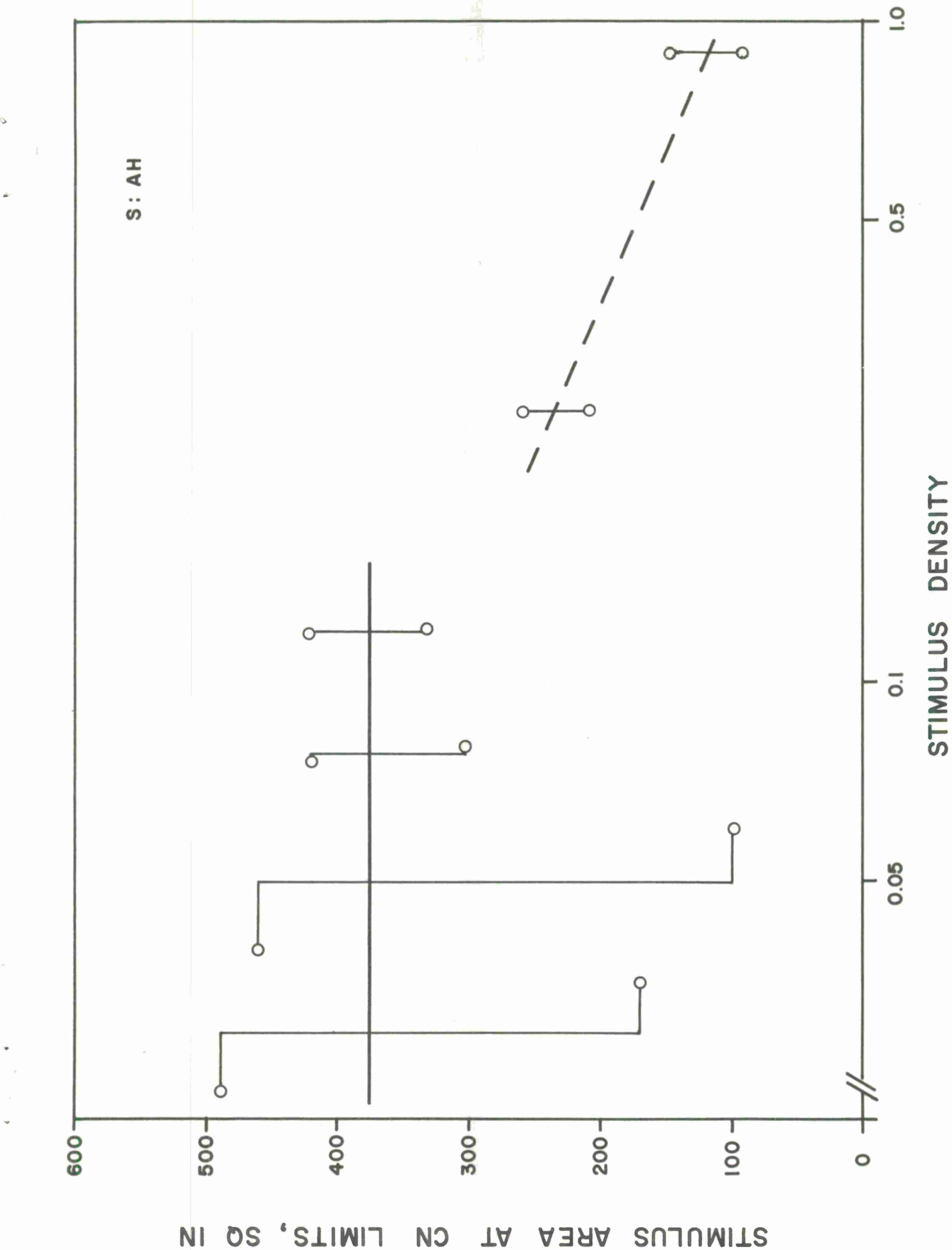

S: AH
STIMULUS DENSITY
0.05
0.1
0.5
1.0
STIMULUS AREA AT CN LIMITS, SQ IN
0
100
200
300
400
500
600

Fig. 5

Showing for subject NCo the stimulus area that is covered by the CN limits, as a function of stimulus density. The axes are semi-logarithmic.

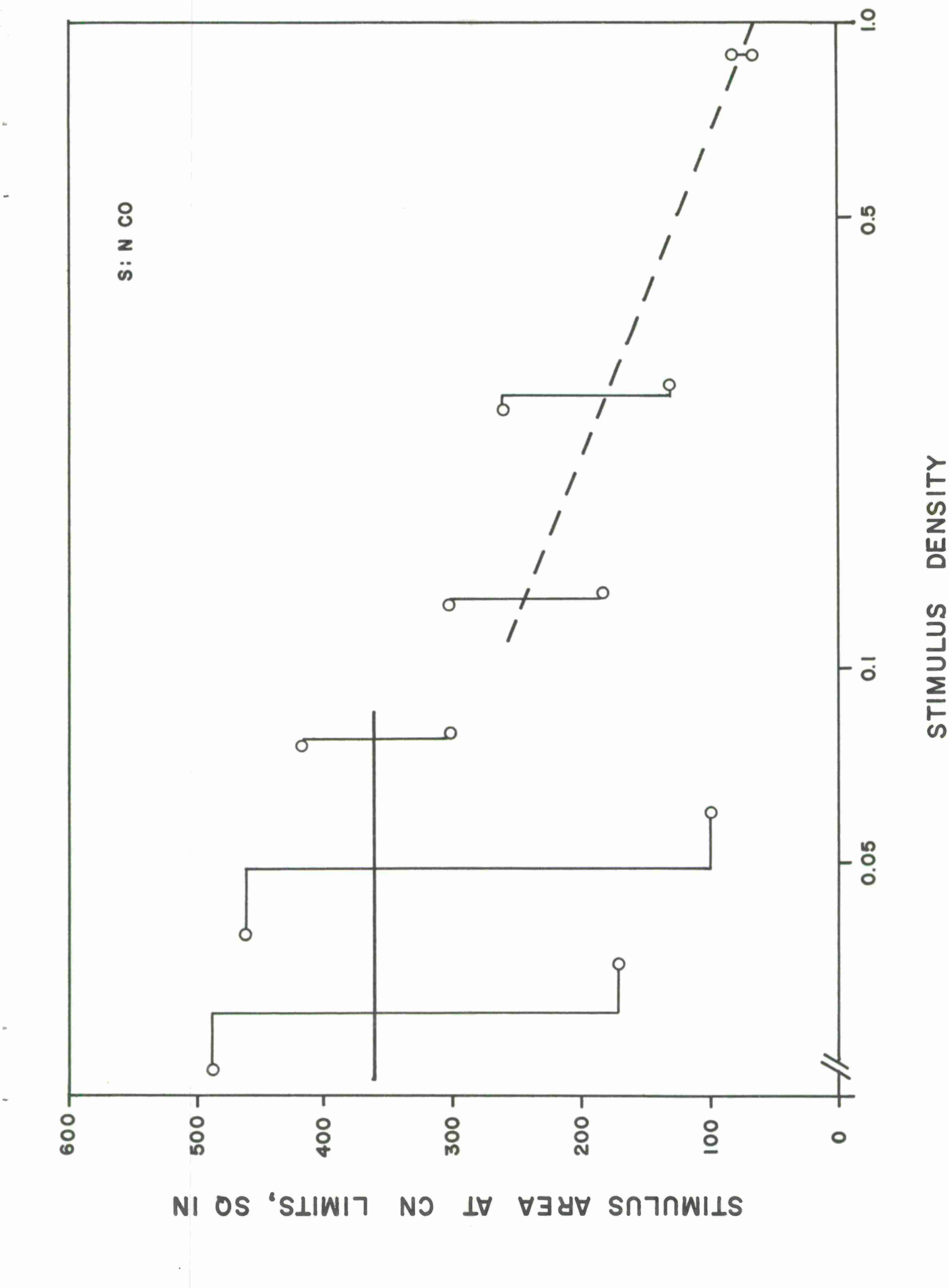

S: N CO
STIMULUS DENSITY
0.05
0.1
0.5
1.0
STIMULUS AREA AT CN LIMITS, SQ IN
0
100
200
300
400
500
600

Fig. 6

Showing for subject NCa the stimulus area that is covered by the CN limits, as a function of stimulus density. The axes are semi-logarithmic.

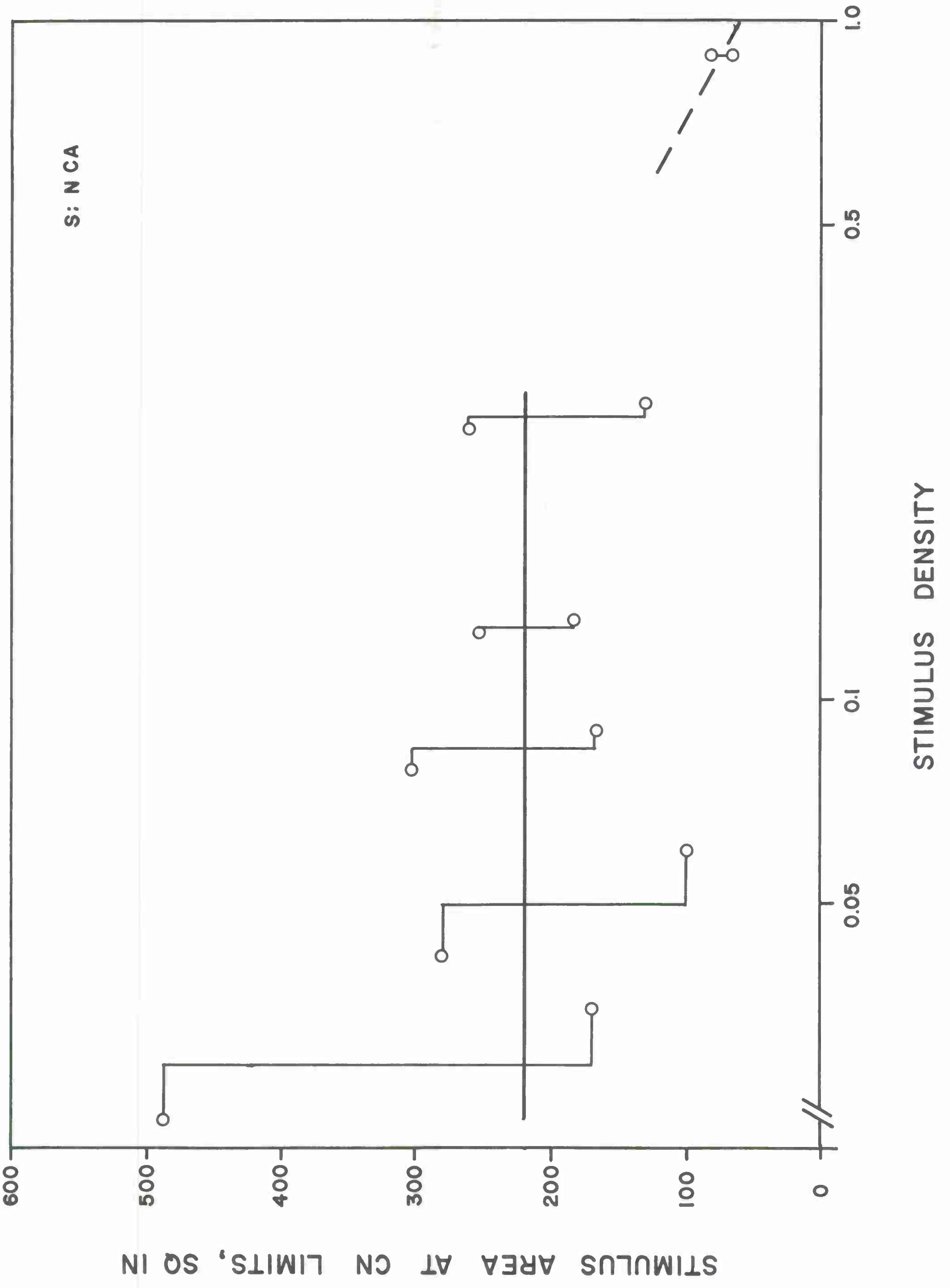
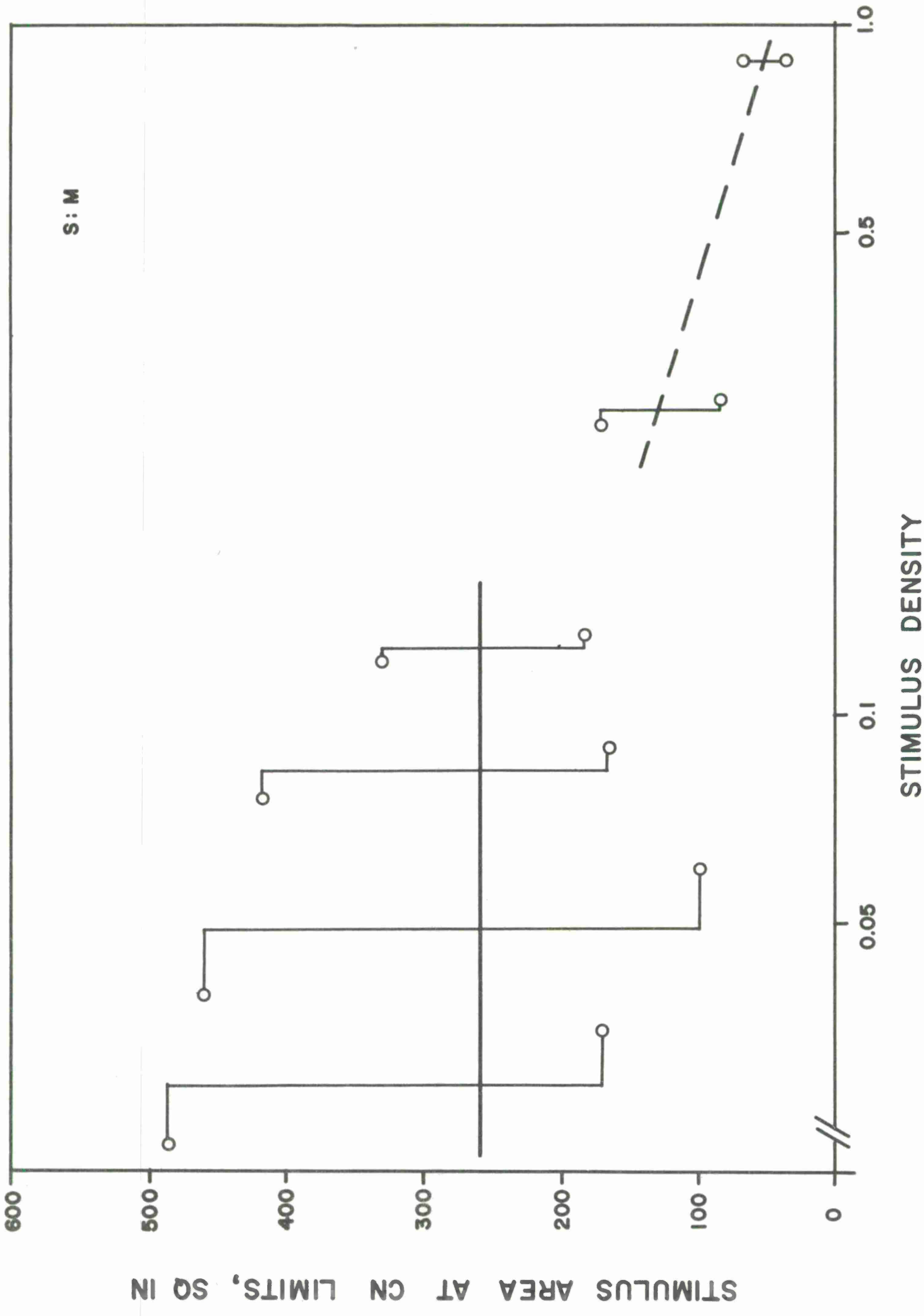

S: N CA
STIMULUS DENSITY
0.05
0.1
0.5
1.0
STIMULUS AREA AT CN LIMITS, SQ IN
0
100
200
300
400
500
600

Fig. 7

Showing for subject M the stimulus area that is covered by the CN limits, as a function of stimulus density. The axes are semi-logarithmic.


S: M
STIMULUS DENSITY
0.05
0.1
0.5
1.0
STIMULUS AREA AT CN LIMITS, SQ IN
0
100
200
300
400
500
600

is limited; it does not matter whether there are fewer elements or more. There is at least one obvious interpretation, as follows. In the density-independent region, the search of one element is not affected by the presence of another. The elements can be separately processed in the fast search, whatever the process may be.

In the density-dependent region, on the other hand, the elements interact in the search process. In our experimental example of triangle-vs-circles, moving the elements closer together within this region makes the triangle harder to isolate and decreases the area of fast search; at the same time the number of elements in this area continues to increase, up to the limit of densities used in this experiment. Perhaps we have come upon a very literal narrowing or concentrating of the field of attention, produced by a relatively more difficult task.

The density-dependent region should be the region of Gestalt phenomena. The most extreme of these is complete embedment; in order to find an embedded form, it may actually be necessary to block off the surrounding, embedding forms with a mask. There are also negative effects that fall far short of embedment; the density-dependent region in this experiment presumably reflects some of these negative effects, whether or not they are considered to be Gestalt effects. By using the fairly elaborate quantitative method of this experiment we can determine the presence, the amount and the limits of negative effects; for example, the limiting density that divides the density-dependent region from the density-independent region.

Most probably the elements of a matrix can interact positively as well as negatively, with respect to search. Imagine a matrix composed of short line-segments, tilted 20 degrees clockwise from the vertical. One segment in the matrix is tilted 5 degrees more, and the task of S is to find this one. The task should be made easier, not harder, by increasing the density of the matrix.

We have examined experimentally only one discriminable characteristic, the form-discrimination of triangle vs. circles. It may still be rewarding to guess about other discriminable characteristics, for the benefit of future experiments and experimenters. Some of the guesses follow. All of the graphs corresponding to Figs. 4-7 will have two branches. A density-independent region will be found for each discriminable characteristic. Different discriminable characteristics will have different curves in the density-dependent region; as noted above, some discriminations should be aided, rather than retarded, by higher stimulus densities. The size of the stimulus difference between the critical and the background elements will be an important parameter. For very large stimulus differences, in the density-independent region, the area of fast search may be the <u>same</u> for different discriminable characteristics. If the area is the same, it will be important to determine this area as a function of viewing distance; it may be constant in terms of visual angle at something like the mean of 10° noted above, or it may be related to apparent visual size. All of these are mere guesses, and worth no more than that.

The finding of a constant area of fast search might lead to a quite different trend of thinking. Perhaps this is the area within which a triangle is discriminable from a circle, with stimuli of our dimensions and with our viewing conditions. Visual acuity drops off very rapidly from its peak at central fixation, and at some viewing angle the triangle and circle would both become a blurred spot. The area of fast search would then be limited only by the acuity for single forms. This would still be an interesting finding, but one that is not contemplated in some of the guesses offered above.

It is our impression that a single triangle can be discriminated from a single circle within a larger area than the one that we have found for fast search. In order to decide the matter, one would need to develop a method of form-perimetry applicable to our experimental situation. There would be only two possible stimuli, a triangle and a circle; the S would have no uncertainty about the location of those stimuli. It would be necessary, nevertheless, to control S's central fixation with some care. We hope to devise this control as a part of a current project on eye-movement photography, and to pursue the problem further. Some operational analysis is also called for. It is quite possible that the only difference between the situation we are calling <u>search</u> and the one we are calling <u>acuity</u> lies in the conditions of S's uncertainty regarding the location of the stimuli.

Next we shall consider briefly the second dependent variable in the experiment, basal time. All five S's gave basal times that were constant as a function of stimulus density, or very nearly so. Fig. 8 shows a plot for one S, AH. The trend line rises only 0.02 sec. over the range of densities employed in the experiment. Different S's gave somewhat different basal times; for example, 0.50 sec. for this S, and 0.71 sec. for M. (See Table III).

The basal time obviously includes some apparatus-delays and some fixed times of stimulation and responding. It also includes the time taken by the process of fast search to cover its characteristic area. It seems reasonable that this time should be constant over the density-independent region referred to above. The plots suggest that it is also constant over the whole range of densities, including the density-dependent region. Perhaps finer measurements would draw out a different picture. Our measurements are not fine enough to answer a number of penetrating questions; for example, does the process of fast search begin at the fixation point and spread rapidly over

Fig. 8

Showing for subject AH the basal time as a function of stimulus density. The axes are semi-logarithmic. Basal time is very nearly constant.

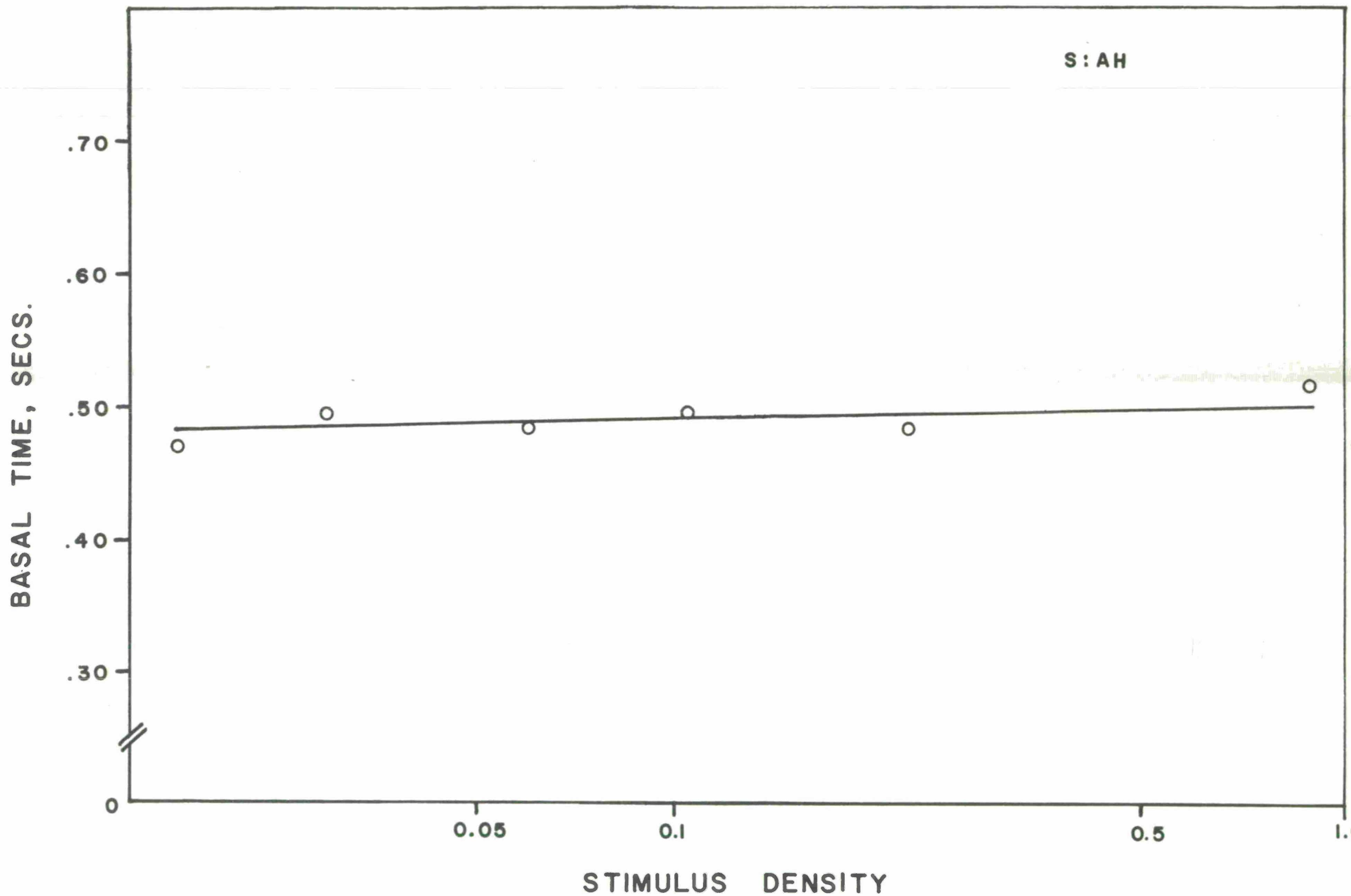

S : AH
.70
.60
.50
.40
.30
0
0.05
0.1
0.5
1.0
BASAL TIME, SECS.
STIMULUS DENSITY

Table III

Showing for each density-range and each S the basal time in seconds. The basal time is the mean of the latencies for points lying below the transition in graphs corresponding to the graph of Fig. 2.

Density	Basal times AH	EW	NCo	NCa	SM
0.890-0.890	.518	.544	.510	.542	.716
0.224-0.319	.484	.540	.498	.590	.726
0.104-0.148	.496	--	.490	.583	.730
0.062-0.095	.483	--	.520	.585	--
0.030-0.060	.495	.580	.500	.530	.710
0.018-0.035	.470	--	.500	.550	.690

the characteristic area?

Because the process of fast search is area-limited at low densities, it should be possible to produce matrices of large area and low density, most of whose elements lie outside the area of fast search. These matrices should yield long search times, on the average, since the critical element will not usually be found with the initial fixation and fast search. The earlier study by Burke and Smith in our laboratory yielded median times of about 1.5 sec. for a large area, a low density, and (obviously) a small number of elements. The evidence is merely suggestive, because their study differed from the present one in two important respects: they used a different discrimination (large circle vs. small circles), and the S's had no uncertainty regarding the area to be presented.

The times for responding to triangles located at the fixation-point are in general about the same as the basal times, and aid in locating the basal times when few points are available for doing this independently. Some of these times for central locations appear in Fig. 2.

Our method of studying search has yielded some interesting results. Yet it has two features that may seem to be arbitrary: only one element is very different from the rest, and all of the rest are identical. Regarding the first feature: it might be interesting to employ more than one critical element, but it would not be easy to determine when each one was first seen. The method runs into complications. Regarding the second feature (the homogeneity of the background elements), it would be especially interesting to vary it systematically, but the method of doing so needs some thought. At any rate, the present method has seemed to us the way to begin. We do not claim that it is the one best way to study search.

III A check-experiment with identical stimulus loci

The last experiment had interesting results: a constant area of fast search within a range of lower densities, and a constant basal time. We decided to check these results by using a somewhat different method. In addition, we wanted to find out something about the shape of this area of fast search, a topic already introduced in the preceding report. The same experimenters, Miss Johanson and Miss McKane, prepared the stimulus material and conducted the experiment.

This experiment and the last one were the same in many ways: the discrimination of triangle vs. circles; the original, high-density matrix of solid black circles; the method of reducing density and area, by peeling off internal and external rows and columns; the dimensions of the elements as projected on the screen. The circles were 9/16 in. in diameter and the distance between their centers was 1 1/16 in., as projected on the screen in the original high-density matrix. This distance varied, and was considerably larger, in the actual stimulus matrices employed. The external shape of the matrices was the same: a rectangle of about 2:1 ratio, height to width. Both density and area varied in the course of stimulation, as before. There was complete randomization of the order of presentation, as before. The apparatus, the instructions, and the methods of presentation, response and timing: these were all the same as before. The S's uncertainties regarding the next exposure were consequently the same as before. Three of the S's in the preceding experiment also served in this one.

Nevertheless there were important differences. The experiment dealt with only the four lower densities of the former six. With the exception of one point for one S, referred to below, the four densities lay in the density-independent regions of the curves relating density to the CN limits (Figs. 4-7). Another difference: the locations of the critical element were chosen from the basic dense matrix so as to provide locations common to two or more densities. This feature permits a close comparison of the latencies for different densities. Lastly, the method of analysis was different. It was designed to yield information about the shape of the region of fast search, as well as the area of that region.

Table IV contains, for each density, the stimulus positions in terms of the original dense matrix, and the corresponding median latencies for each of the three S's. The different stimulus areas are combined in producing the tabular entries. The number of observations per density per location per S was 16, hence the medians are based on an N of 16. The total number of observations in the experiment was 16,512.

As an overall display of their measurements, the experimenters made a three-dimensional model for each of the S's. In the model, the height of a 1/4 in. wooden peg represents the median latency for a given S, location and density. Where the peg is put on the base represents the corresponding location of the critical element. Fig. 9 shows a photograph of one of the models, as viewed obliquely from above. The pegs are colored to indicate stimulus density, but the color cannot be reproduced in this report.

All three models have the same general shape, which may be seen in the figure. There is a low, flattened area in the middle, looking like stumps in a dry pond; this is the region of short times and fast search. The clumps of longer times rise to the sides and especially to the ends of the

Table IV

Showing for each of four density ranges and for each position of the critical element the corresponding median latency for each of three subjects. Position is defined in terms of a master matrix 57 elements wide and 33 high, of the highest density used in the experiment of section II. Thus, 11,5 designates a critical element (triangle) in the 11th column from the left and the 5th row from the top of the master matrix, regardless of its position in the actual stimulus matrix of a given area and density. The latencies for one position 29,23, (density 0.062-0.095) are bracketed and omitted from the peg-model and graphs, because of defects in a stimulus sheet.

TABLE IV

Density 0.104-0.148

STIMULUS POSITION	MEDIAN LATENCY, for S's: NCo	AH	M
5,5	2.09	1.48	2.97
11,5	.86	.58	1.18
17,5	2.02	1.57	2.29
29,5	1.97	1.98	2.35
41,5	1.58	2.51	1.99
53,5	1.78	1.70	2.00
5,8	2.10	1.32	2.59
51,8	1.67	1.74	1.76
5,11	2.14	1.34	2.25
11,11	1.88	1.17	2.12
17,11	1.36	1.14	1.42
23,11	.86	.73	1.03
29,11	.73	.60	1.06
35,11	.83	1.27	.97
37,11	1.02	1.52	1.38
41,11	.95	1.85	1.34
47,11	1.08	1.57	1.51
53,11	1.40	1.89	1.76
5,17	1.96	1.07	1.86
14,17	1.27	.90	1.18
17,17	.82	.65	.95
29,17	.52	.50	.65
41,17	.80	.94	.90
44,17	.92	1.12	1.13
53,17	1.26	1.44	1.30
5,23	2.14	1.33	2.25
11,23	1.70	1.01	1.82
17,23	1.22	.98	1.14
23,23	.67	.88	.84
29,23	.67	.60	.82
35,23	.65	.76	.85
41,23	1.21	1.12	1.04
47,23	1.49	1.12	1.33
51,23	1.42	1.16	1.44
53,23	1.96	1.53	1.64
5,29	2.65	1.49	2.48
17,29	2.40	1.68	1.69
29,29	1.25	2.48	1.32
41,29	1.75	1.78	1.33
53,29	2.33	1.57	1.52

TABLE IV, cont'd.

Density 0.062-0.095

STIMULUS POSITION	MEDIAN LATENCY, for S's: NCo	AH	M	STIMULUS POSITION	MEDIAN LATENCY, for S's: NCo	AH	M
5,5	1.76	1.15	2.53	37,17	.64	.57	.74
11,5	.86	.58	1.18	39,17	.82	.80	.82
25,5	1.66	2.07	2.10	41,17	.81	.79	.87
29,5	1.71	1.24	2.00	45,17	1.06	.75	1.12
33,5	1.72	1.45	1.84	47,17	.87	.88	1.02
53,5	1.58	1.67	1.88	49,17	1.05	1.00	1.25
5,7	1.91	1.18	2.35	51,17	1.12	1.23	1.79
13,7	.96	.67	1.09	53,17	.94	1.32	1.18
33,7	.55	.51	.75	57,17	2.08	2.04	2.91
5,11	2.07	1.07	2.12	11,23	1.39	.91	1.31
11,11	1.07	.85	1.66	23,23	.60	.60	.79
17,11	1.58	1.22	1.25	29,23	(2.20)	(2.12)	(2.11)
23,11	.70	.58	.90	35,23	.61	.55	.76
29,11	.72	.58	.93	47,23	1.30	.91	1.08
35,11	.72	.63	.86	5,27	2.46	1.31	2.49
41,11	1.02	1.47	1.15	17,27	2.04	2.14	1.82
45,11	.74	.75	.88	29,27	1.38	1.96	1.12
47,11	.94	1.04	1.31	41,27	1.88	1.80	1.26
53,11	1.16	1.80	1.74	53,27	2.16	1.45	2.10
35,13	.59	.50	.70	5,29	1.73	1.23	2.15
1,17	2.41	1.08	2.42	13,29	1.72	1.27	1.63
5,17	1.46	.97	1.58	17,29	1.61	1.30	1.34
9,17	1.62	.93	1.46	25,29	1.07	1.68	1.20
13,17	1.39	.83	1.19	29,29	1.03	1.22	1.13
17,17	.68	.60	.86	33,29	.91	1.19	1.19
21,17	.68	.52	.76	41,29	1.36	1.20	1.20
25,17	.55	.48	.73	43,29	1.65	1.32	1.19
29,17	.50	.49	.63	47,29	1.47	1.35	1.21
31,17	.52	.47	.66	51,29	2.06	1.44	1.43
33,17	.55	.52	.71				

TABLE IV, cont'd.

Density 0.030-0.060

STIMULUS POSITION	MEDIAN LATENCY, for S's: NCo	AH	M
5,5	1.44	.98	2.01
17,5	1.33	.91	1.69
29,5	1.24	.89	1.71
41,5	1.23	1.20	1.46
53,5	1.15	1.26	1.46
17,9	.63	.50	.87
41,9	.74	.53	.77
5,11	1.61	1.09	1.76
11,11	1.04	.86	1.45
17,11	.87	.80	1.11
23,11	.62	.56	.92
29,11	.66	.54	.90
35,11	.63	.61	.82
41,11	.87	1.24	.98
47,11	1.00	1.10	1.33
53,11	1.03	1.35	1.29
5,17	1.12	.95	1.66
17,17	.64	.55	.87
29,17	.53	.50	.62
41,17	.76	.60	.88
53,17	1.09	1.20	1.28
5,23	1.65	1.05	1.88
11,23	1.22	1.01	1.44
17,23	.80	.76	.96
23,23	.58	.52	.80
29,23	.59	.57	.83
35,23	.58	.58	.85
41,23	.98	1.01	.92
47,23	1.64	1.41	1.15
53,23	1.14	1.23	1.33
5,29	1.80	1.13	1.83
17,29	1.62	1.06	1.20
29,29	.82	1.32	1.29
41,29	1.38	1.13	1.20
53,29	1.41	1.29	1.30

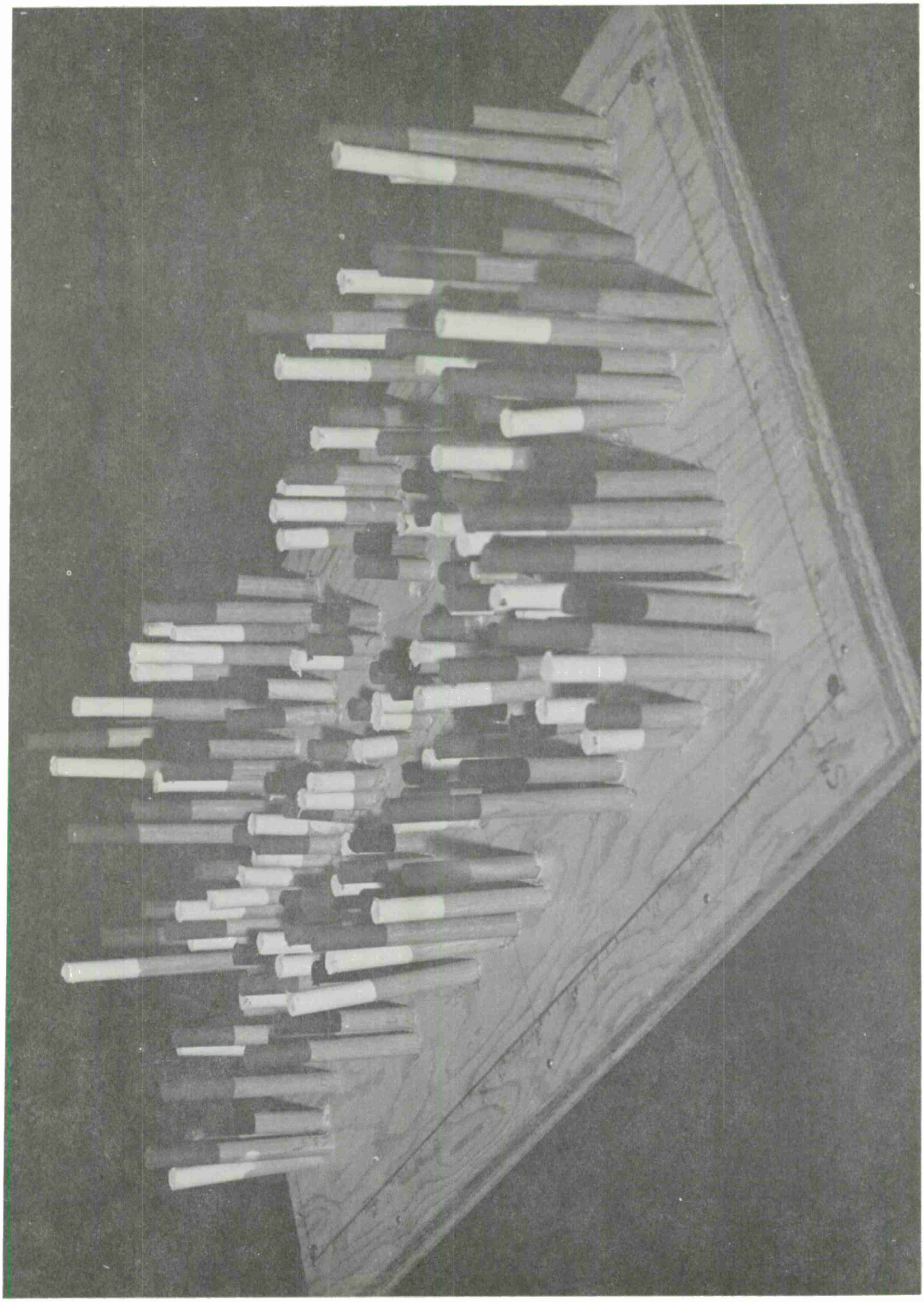
TABLE IV, cont'd.

Density 0.018-0.035

STIMULUS POSITION	MEDIAN LATENCY, for S's: NCo	AH	M
5,5	1.61	.96	1.90
17,5	1.07	.74	1.50
25,5	1.23	.71	1.59
29,5	1.02	.84	1.44
33,5	1.11	.96	1.50
41,5	1.23	1.40	1.34
53,5	1.28	1.58	1.54
1,17	1.76	1.06	2.24
5,17	1.41	.94	1.87
9,17	1.17	.77	1.42
13,17	.82	.65	.93
17,17	.62	.51	.85
21,17	.58	.50	.76
25,17	.52	.49	.65
29,17	.50	.49	.66
33,17	.53	.49	.71
37,17	.58	.51	.73
41,17	.62	.56	.77
45,17	.86	.75	.87
49,17	.99	.89	1.19
53,17	1.38	1.37	1.38
57,17	1.62	1.39	1.48
5,29	1.82	.92	1.49
13,29	1.24	.82	1.30
25,29	.90	.87	1.21
33,29	.71	.94	.90
41,29	1.14	1.08	.96
53,29	1.26	1.25	1.30

Fig. 9

A photograph of a peg-model representing the results of one subject. The height of the pegs represents median latency in secs. The location of the peg on the board represents the location of the critical element in the dense master matrix. Clumps of pegs represent identical stimulus loci in matrices of different densities. In the actual model the pegs of different colors represent different densities; the colors cannot be reproduced here. Refer to the text for a discussion of the shape of the peg-model.



display. Here the search must be successive, consisting of a series of fixations and fast searches before the triangle appears. It appears presumably as a figure in a ground of circles. The occurrence of fast search in a particular area is consequently a condition for the appearance of a figure in that area. In saying this, we are not saying much more than attention may control the appearance of a figure, or that fixation may do so (as in a reversible figure). More work on the area of fast search might provide a genuine advance over the older statements.

The analysis can proceed most directly by using a central portion of the data, namely the latencies from the long middle row of the matrix. Figs. 10-12 inclusive show these latencies for all three S's, and for almost all of the densities. The figures are keyed for density. One density has not been plotted for one S, (NCo), because in Fig. 5 from the first experiment this density did not lie on the density-invariant portion of the curve.

The mass of all points on each graph describes a course that is concave upward, as would be expected from the photograph of the model, Fig. 9. It would be easy to draw a single trend-line through the mass. Nevertheless it is also possible to distinguish a group of points at the bottom of the graph as being slightly different from the rest: they lie inside a narrower band, within about 0.2 sec. of the basal time. We believe that this narrow band of short latencies represents the area of initial fast search, and that it corresponds to the range of nearly constant latencies in Fig. 2 from the first experiment. The narrow band can be made out in the graphs for all three S's; the greatest uncertainty attaches to the left end of the band for NCo in Fig. 10, where the band could easily be extended by one group of points. Not all densities are represented at all stimulus positions, but the narrow band is not due to this fact. Two densities (0.062-0.095) and (0.018-0.035) are represented at most stimulus positions; plots of

Fig. 10

Showing for one subject, NCo, the median latency for each position of the critical element in the middle or 17-row of the master matrix. The different densities are coded separately, as indicated by the key. Both axes are arithmetic. The highest of the four densities is omitted from this graph, because it fell outside the density-independent range for this subject. Refer to the text for a discussion of this and the following two figures.

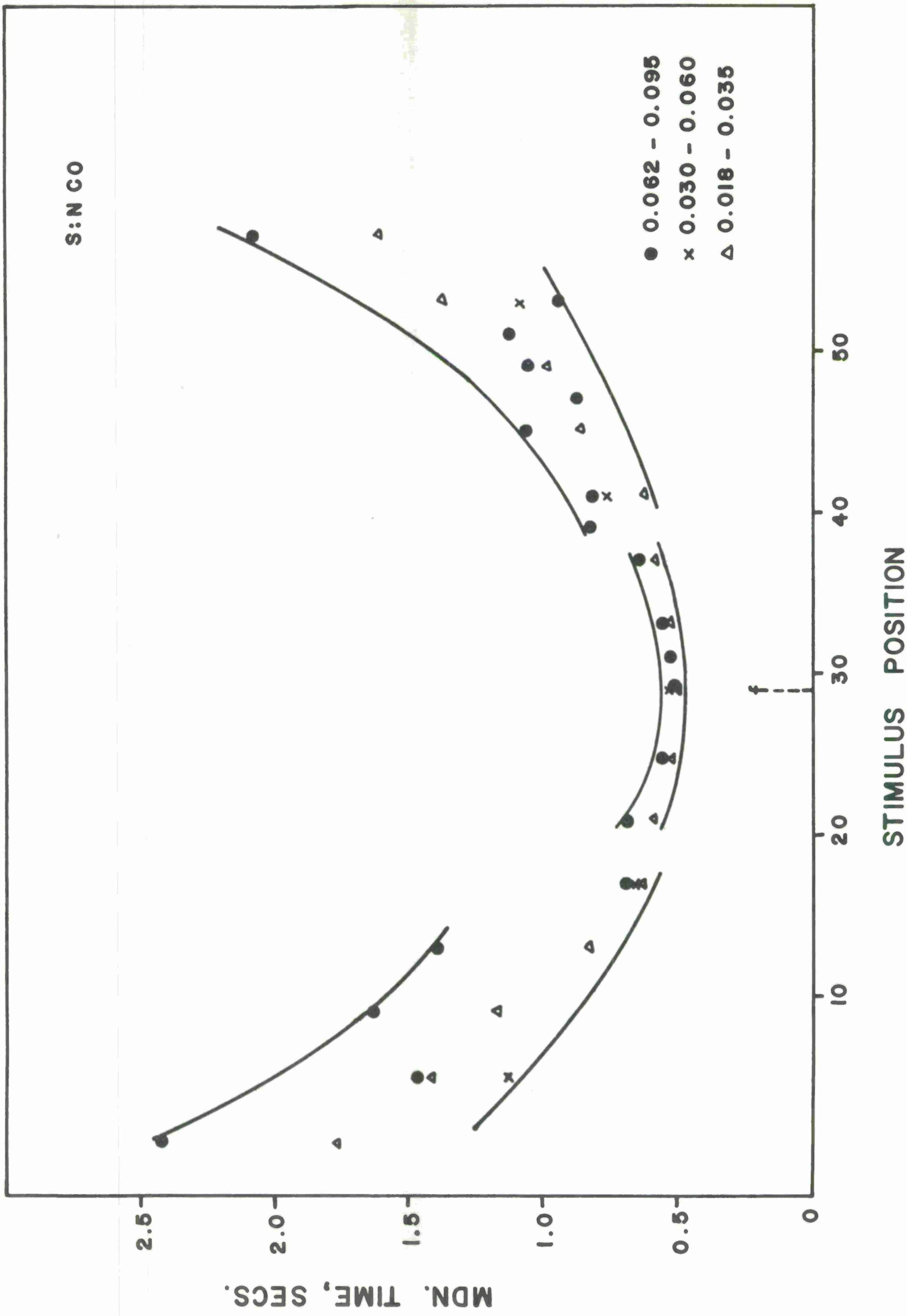

S: N CO
● 0.062 - 0.095
× 0.030 - 0.060
Δ 0.018 - 0.035
MDN. TIME, SECS.
0
0.5
1.0
1.5
2.0
2.5
10
20
30
40
50
f
STIMULUS POSITION

Fig. 11

Showing for one subject, AH, the median latency for each position of the critical element in the middle or 17-row of the master matrix. The different densities are coded separately, as indicated by the key. Both axes are arithmetic. Refer to the text for discussion of the figure.

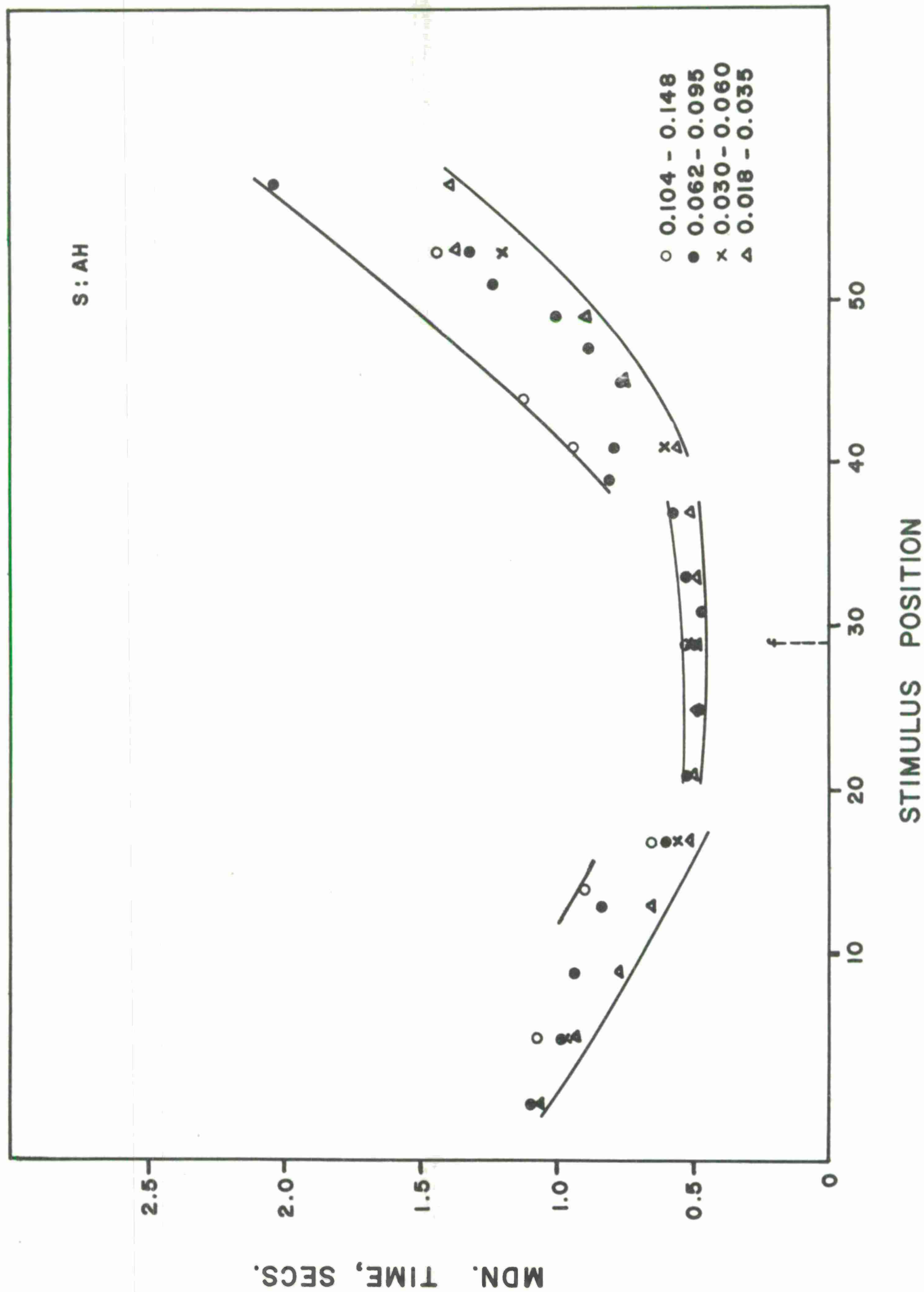
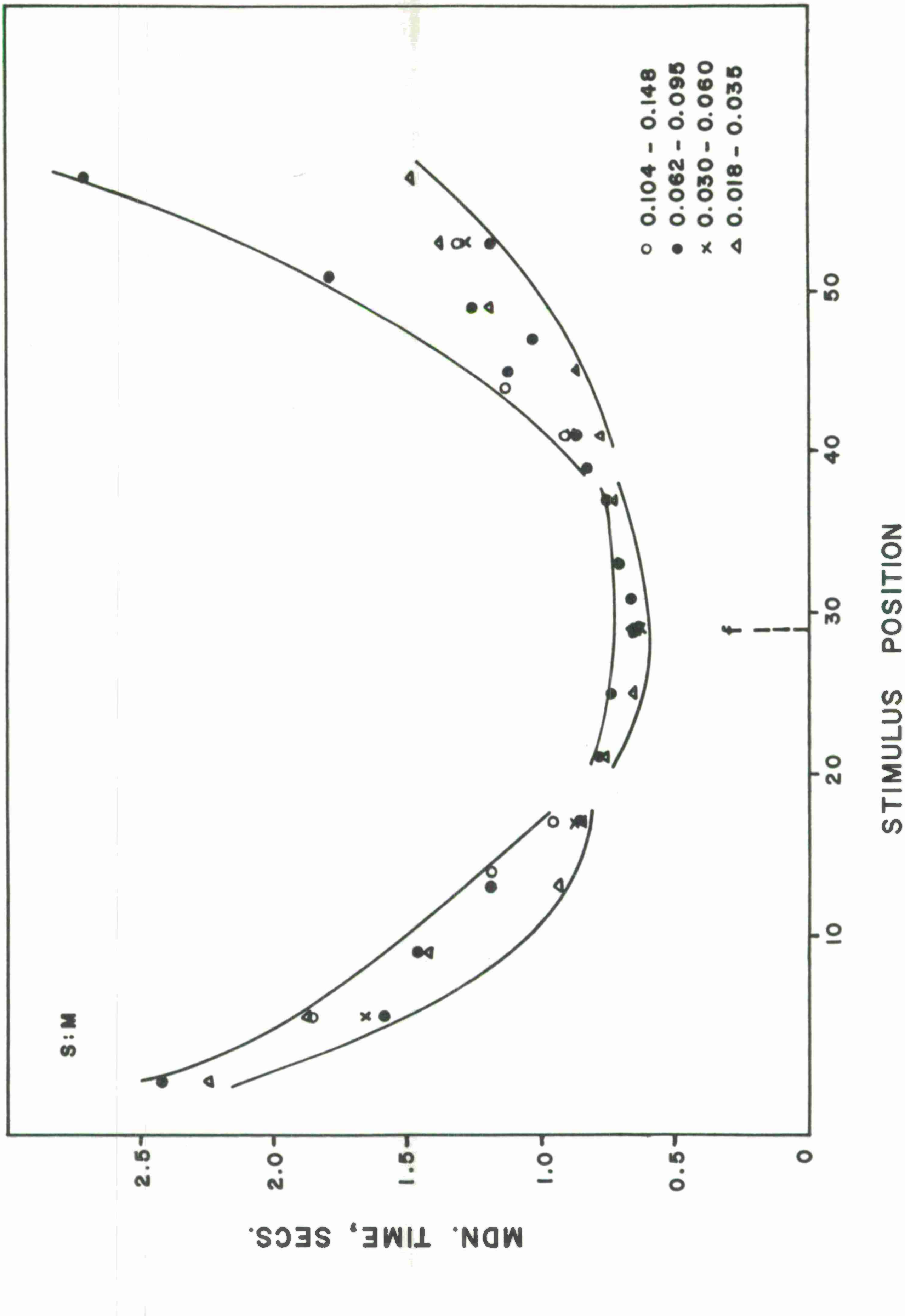

S: AH
○ 0.104 - 0.148
● 0.062 - 0.095
× 0.030 - 0.060
△ 0.018 - 0.035
STIMULUS POSITION
MDN. TIME, SECS.
0
0.5
1.0
1.5
2.0
2.5
10
20
30
40
50

Fig. 12

Showing for one subject, M, the median latency for each position of the critical element in the middle or 17-row of the master matrix. The different densities are coded separately, as indicated by the key. Both axes are arithmetic. Refer to the text for discussion of the figure.


S:M
0.104 - 0.148
0.062 - 0.095
0.030 - 0.060
0.018 - 0.035
f
10
20
30
40
50
STIMULUS POSITION
0
0.5
1.0
1.5
2.0
2.5
MDN. TIME, SECS.

these densities alone have much the same appearance as Figs. 10-12. Some of the reasons for the broad bands at the sides of the graphs will appear below.

The graphs provide a check of one finding immediately: the basal times are the same for all of the densities used in the experiment. The basal time is the center of the narrow band, at its minimum. As an incidental finding: the basal time is stable for each of these three S's, from one experiment to the next; the paired times for the two experiments are, respectively, 0.49 and 0.50 sec.; 0.50 and 0.52 sec.; 0.71 and 0.65 sec.

The next check is more important, but less certain. It concerns the finding of an area of fast search that is invariant over a range of low densities (the range examined in this experiment). If the area does not change with density, and if its shape also does not change, its horizontal diameter as read off the coordinates of Figs. 10-12 should not change with density. The fact that one can draw the bands in the first place is one indication that the diameter does not change. There is a complication: not all densities are represented at all stimulus positions, as noted above. Nevertheless, (as also noted above) two of the densities are represented at most positions, and narrow bands with the same limits can be drawn for these two densities. One could wish for a more sensitive check, but (such as it is) its indication is positive.

At this point another check is in order: we should ask whether the areas marked out by the graphical method of the last experiment, and the different graphical method of this one, are about the same. Are we dealing with the same area of search, or a different one? To answer the question, it is necessary to measure approximately the vertical diameter of the area in the present experiment, using the same graphical method represented in Figs. 10-12; also, to assume a geometrical shape for the area. The very approximate measurement of vertical diameter was 18 in. for both S's NCo and AH; none could be obtained for M. The shape assumed for the area was a regular ellipse. The computed area is 286 sq. in. for each of the S's NCo and AH. The corresponding areas from the preceeding experiment are 362 and 377 sq. in. for the two S's respectively. The agreement is fair, considering the differences in assumptions and method; the chances are that we are dealing with the same area of fast search.

The bands at the sides of Figs. 10-12 are broader than the band at the bottom for two reasons. First, the latencies become more variable as they lengthen, because the search must be successive. The triangle cannot be seen on the initial fast search, and must be found by repeated fixations and fast searches. The pattern of successive search is intrinsically variable, because the search can go in several directions from any of the successive fixations. The new direction may lead toward the triangle or directly away from it. Secondly, the density of the matrix affects the latencies outside the area of fast search; this is true even of densities in the density-independent range of area. Higher densities take longer to search. For evidence, we can compare the latencies for the density range 0.062-0.095 with those for the density-range 0.018-0.035, and apply a sign test; only the points in the bands at the sides of the graphs are considered. Of the 29 valid comparisons, the higher density has the longer latency in 25, a result significant at the .001 level in a one-tailed test.

The _shape_ of the area of fast search is an interesting problem in its own right. At one time during the experiments it seemed to us quite possible that the area could have nearly any shape, and that the shape would depend upon the S's uncertainty with respect to the location of the critical element. In rectangular matrices of 2:1 ratio, width to height, like those of the present experiment, the area of fast search would then be rectangular or oval, with a 2:1 ratio of diameters. First inspection of the peg-models suggested a considerably flattened shape, like that one. Nevertheless, the detailed graphical analysis did not support it. The horizontal and vertical diameters, as approximated from the graphs, are respectively 20.2 in. and 18 in. for both NCo and AH. This is nothing like 2:1. Instead, the result agrees quite well with the description of shape given by Chaikin _et al_.: ovaloid, with the longer axis horizontal.[3]

Apparently the gross shape of the peg-models, as seen for example in Fig. 9, is due more to the statistical pattern of _successive_ search than to the shape of the area of fast search. It is eminently reasonable that the pattern of successive search should be controlled by the S's spatial uncertainties concerning the exposure to come. Some fairly simple experiments could verify the statement; they would employ matrices of different external shapes, presented in blocks.

It is clear from the data of the preceding report that the shape of the area of fast search is not determined by the shape of the individual stimulus array, apart from the S's uncertainties regarding it. Table I, p.81, of that report shows mainly lower CN's for bar-shaped stimulus matrices than for square ones. The bar-shaped stimulus has not flattened out the area of search, but rather has cut across it at one angle or another. The former experiment did not test the role of spatial uncertainty, because S did not know how the stimulus bars would be oriented in the next exposure: vertically, horizontally, or diagonally.

IV Two exploratory experiments and their methodological implications

This section describes very briefly two experiments dealing with the area of fast search. The first one attempted to find a simpler and more economical way of marking off the area and determining its shape. The second experiment, using a method that was anything but simple and economical, aimed to illuminate a particular problem: the expansion of the area of fast search with increased exposure time, reported by Chaikin _et al_.[3] The experiments ran concurrently with the first two experiments of this report, so that they did not benefit from the results now in hand. Nevertheless, one can find some methodological implications in all of the experiments considered together, and this section will state them.

Miss Joy Halfter conducted the first experiment. The principle aim was to economize on the presentation of whole matrices, and to avoid its attendant necessity of sampling the locations of the critical element. Both the method of lasting exposures and the method of brief exposures, described in the preceding report (p. 29), require the presentation of whole matrices. Economy is indicated, because in some experimental designs 20 or 30 hours of experimentation per S are still insufficient to produce an adequate number of observations.

The idea was to present reduced matrices, consisting of a single line of elements. The critical elements could be located at all positions in the line; the sample of locations could thus be a total sample. The _inclination_ of the line could be varied at random from one exposure to the next, including at least the horizontal, the vertical, and the two diagonals. Inspiration for this method came from the experiment with bar-shaped matrices, described in the preceding report, pp. 80-82. The method might be called a one-line axial method for studying search.

In many ways this experiment was like the preceding two. The S's made the same discrimination of triangle among circles. The dimensions of the individual elements, as projected, were the same. The apparatus, the mode of presentation, the response and the timing were all the same. Most of the instructions were the same.

The experiment was different in that only a single line of 14 elements appeared. These had a single linear density, being 4 5/16 in. apart on centers. In a full matrix, this would have been equal to the density range of 0.062-0.095 from the preceding experiment (an intermediate density). The line appeared at four different inclinations: the horizontal, vertical, and the two diagonals. The triangle always had the same orientation, nevertheless; it rested on a base. The triangle came up in all 14 possible positions at each inclination. Randomization of order was complete over all inclinations and all positions. S knew that the stimulus pattern would be a line, centered about the fixation point; the triangle could lie nearly anywhere inside a circle described by the line as rotated. There were 5 S's.

The median latencies were plotted for each inclination and each S, on graphs similar to Figs. 10-12. Indeed, the two sets of graphs have a similar appearance: a region of short latencies around the fixation point, and considerably longer and more variable latencies at each side. One side tended to have longer latencies than the other, for each S; this suggests that in successive search a given S looked first to one side (say to the right of a horizontal line) and then to the other, if the triangle had not yet appeared. It might be possible to find in this way characteristic individual patterns of successive search.

To determine the diameters of the area of fast search from these data is quite another problem, as yet unsolved. As a first try, we drew smooth curves quite carefully through the data, and then estimated the x-coordinates of the two points of inflection, on the rising slopes at the two sides. The means of the sets of x-coordinates for all S's, when plotted at the proper stimulus inclinations, described a neat circle concentric with the fixation point. This might be viewed as a rough determination of the area of fast search. Yet it is unlikely that the distance between the two points of inflection corresponds well with the diameters as determined by our other methods. Perhaps a distance can be marked off at the bottom of the curve by graphical methods similar to those of the last experiment, but this has not yet been accomplished.

The second exploratory experiment was very different. It started with the finding of Chaikin _et al_. that the area of fast search expanded with increasing exposure time.[3] There is an obvious explanation for this. Chaikin's S's were making a form-discrimination of triangle _vs_. circles; like most acuities, this form-acuity is controlled by the Roscoe-Bunsen Law up to a critical value of exposure-time. It might be better to use a discrimination that is not so controlled, if one could be found. The best candidate seems to be the discrimination of the tilt of short straight lines, on the evidence of Leibowitz, Myers and Grant.[4] The area of fast search might turn out to be independent of exposure time (and presumably also of intensity) within wide ranges of those variables. This would surely be a desirable result.

We should also note certain advantages of the tachistoscopic and liminal method used by Chaikin _et al_. First, the method substantially eliminates successive search, and should therefore delineate fast search more clearly. Tachistoscopic presentation eliminates successive search for two reasons: prolonged search of any kind is impossible, because the exposure does not last that long; also the S soon learns to hold his initial fixation in order to gain maximum information from the brief exposure.[5] The second advantage of Chaikin's method is its relative objectivity, as contrasted with the graphical methods used in most of our experiments so far. Modern detection-theorists would hasten to add that still more objectivity can be gained by using a forced-choice method.

Incited by these ideas, we built a complicated and special apparatus for producing a tachistoscopically exposed 15 x 15 matrix of tilted lines. The tilt of each line in the matrix could be changed manually and rapidly to a value different from all the rest, for the exposure; it could then be restored, and another line could be differentially tilted. Fig. 13 is a photograph of the matrix, taken from the rear or E's side.

The first step in construction was to lay out a 21 x 21 in. brass plate in the matrix pattern, and to cut 225 holes in it. The next one was to die-cut thin black-plastic disks, with a slot in each one to form the tilting line. Small plastic handles were carefully cemented to each disk, with the aid of an assembly jig. Lathe-turned retaining rings held the disks over the holes, and permitted them to rotate about their centers. Stops attached to the rings limited the tilt of the line to the desired values.

The lines in the matrix were 3/4 in. long and 1/8 in. wide, placed 1.400 apart on centers. This is a high density; it might very well lie in a density-dependent range for area if we had the curves necessary to determine this fact.

Fig. 14 shows the apparatus for projecting the matrix and timing its exposure. The projector in the foreground contained no transparency; its beam, somewhat reduced in intensity, was used only to light up the stimulus matrix from the back. The beam was passed by the slots in the large rotating disk. A synchronous motor and reducer drove the disk continuously at 1.0 rps. The circumferential length of the particular slot which passed the beam set

Fig. 13

A photograph of the 15 x 15 stimulus matrix apparatus as seen from the rear or experimenter's side. A mirror-image of the light-colored bars alone would resemble the matrix as seen by the subject. To illustrate a critical element, the bar in the very center of the matrix has been offset clockwise from the vertical. Refer to the text for a further description of this apparatus.

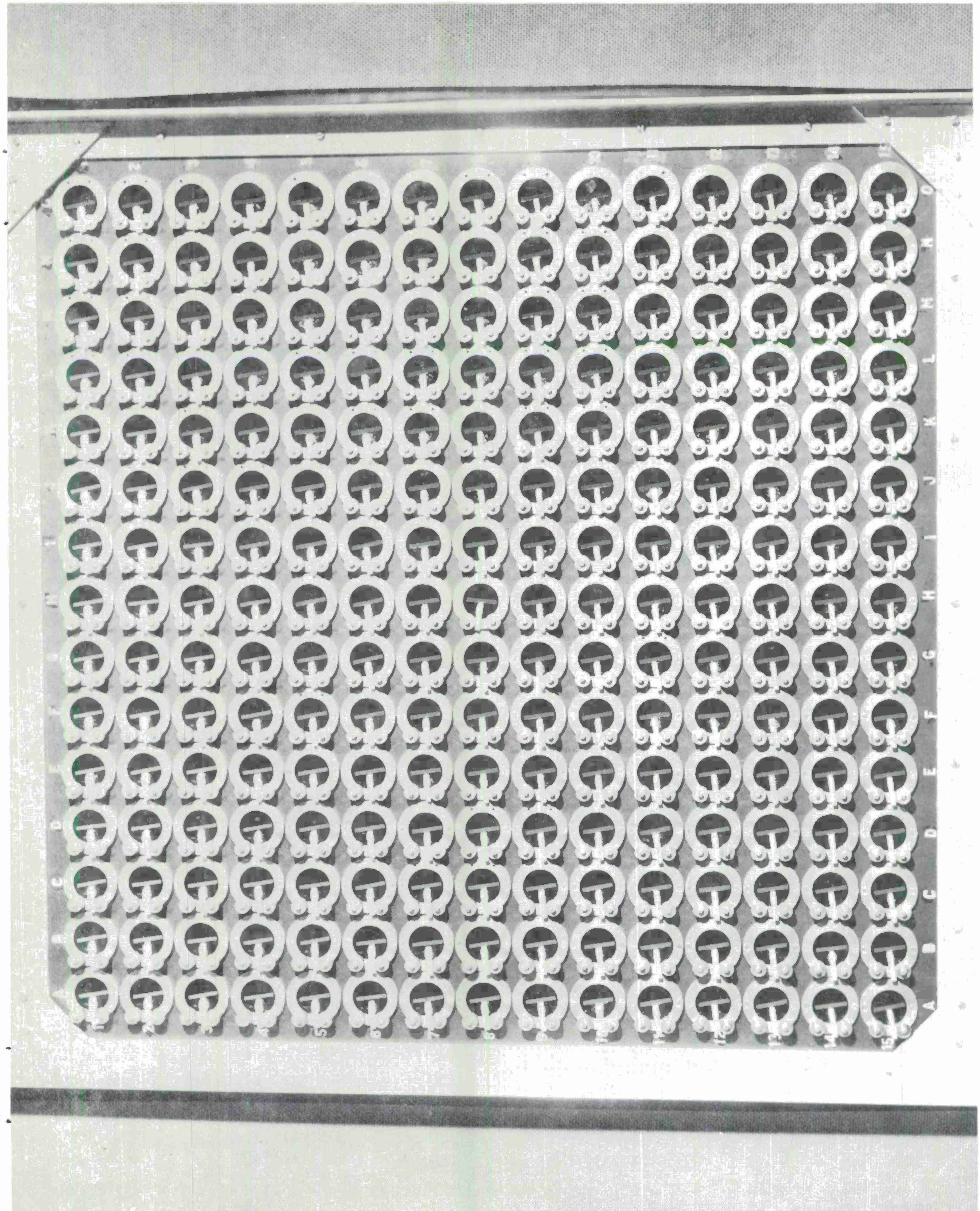
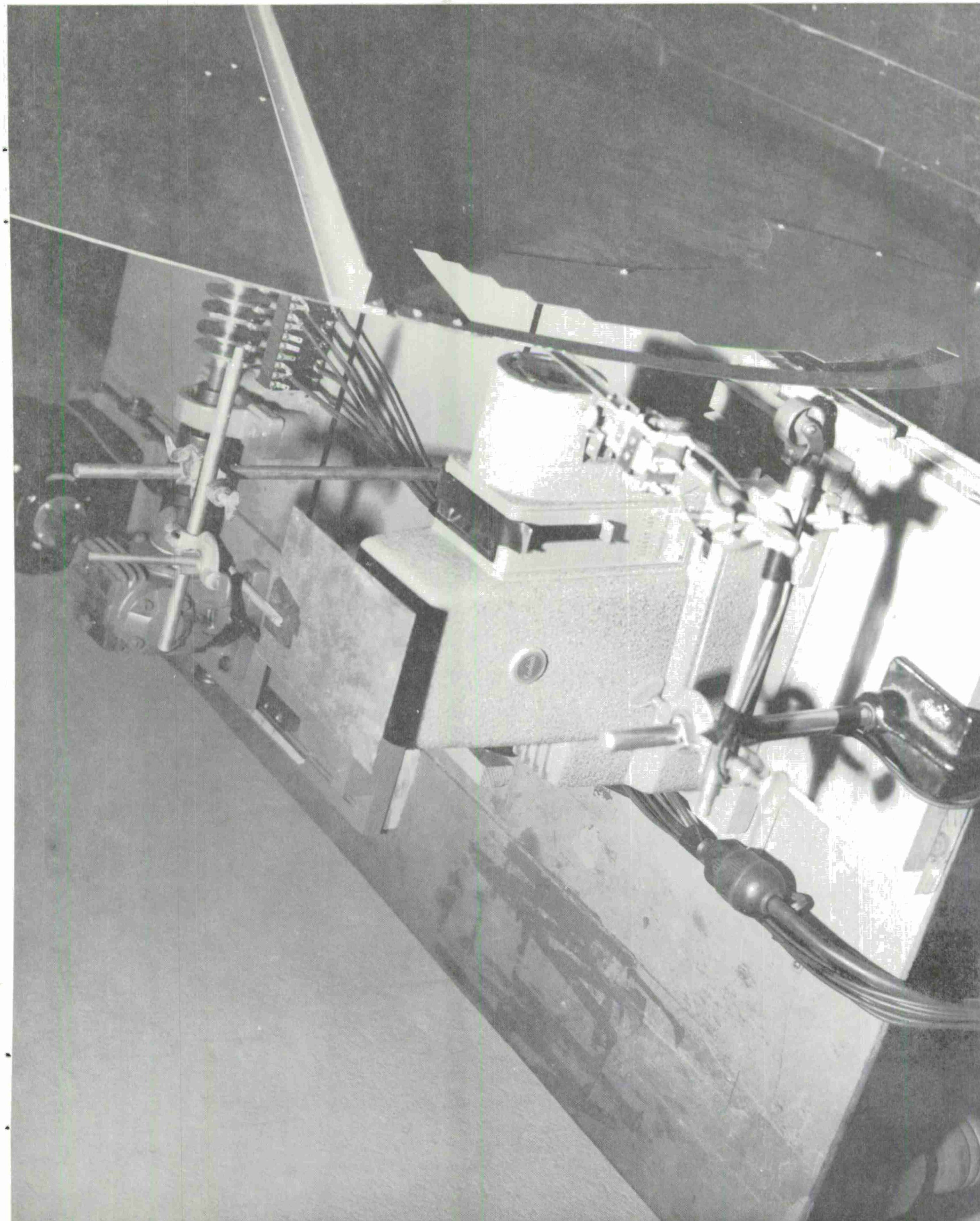


Fig. 14

A photograph of the apparatus for projecting the stimulus matrix and timing its exposure. From top to bottom: the synchronous driving motor, the gear reducer, the cams for timing and control, the large disk that turned continuously at 1 rps, the projector for illuminating the matrix apparatus from the rear, the circumferential slots in the disk that pass the projector beam and produce a timed exposure. Immediately in front of the projector, the small shutter that prevents more than a single exposure at one trial.



the exposure time at one of the 5 values: 6, 10, 20, 50 and 80 millisec. The E selected a particular time by moving over the motor, reducer, disk and bearings as a unit on a carriage, until a slot of the proper length passed in front of the projector; then the carriage was pinned fast. A small shutter in front of the projector prevented more than one exposure from occurring. The entire apparatus was constructed in our laboratory shop, with much labor but small expense; the same product from an outside shop would most probably have taken all of the funds in the contract.

The E set the exposure time and selected the critical stimulus. At the exposure, the projector beam went through the slots in all 225 little disks and produced the stimulus pattern on the center of a rear-projection screen, placed in close contact with the matrix apparatus. The S viewed the stimuli from the front; the viewing conditions were much like those of Chaikin _et al_. A fixation spot appeared in the center of the screen in the dimly-lighted room; at the ready-signal, S fixated it; the matrix appeared briefly, and was succeeded after 1/4 sec. by an erasing field. If S saw the critical element (the line of opposite tilt) she said _yes_; otherwise _no_. If she said _yes_, she then pointed on a white panel of the same shape and size as the matrix to the approximate position of the critical element. The E could see this panel in a mirror; she checked the approximate accuracy of the localization. Some 10% of the exposures were blanks; i.e. no line was differentially tilted. There were 4 S's, who served about 20 hours each. Because the critical element appeared repeatedly in all 225 possible positions in the matrix, this was a very time-consuming method.

In the analysis, the frequency of positive responses was entered in the cells of a matrix corresponding to the stimulus matrix, and a liminal contour was drawn on the basis of the frequencies. Chaikin _et al_. have described and illustrated this procedure in their brief article.[3]

In the initial exploratory experiment, by Miss Kathryn Eppston and Miss Patricia Napper, the stimulus difference was large: the background elements were inclined 11 1/4 degrees clockwise from the vertical, and the critical element 11 1/4 degrees counter-clockwise from the vertical. Tilt-discrimination is sharp around the subjective vertical, which acts as a natural anchoring point. The S's saw the critical element over the entire matrix; no liminal determination was possible. Consequently Miss Napper, in continuing the experiment, was forced to the expedient of reducing the stimulus difference in order to bring the area of fast search within a measurable compass. The background elements were inclined 5 degrees clockwise from the vertical, and the critical element 5 degrees counter-clockwise from the vertical. Because there were still 225 possible positions of the critical element, Miss Napper was able to accumulate an N of only 6 observations per position per S. So the experiment should be regarded as exploratory.

The results can be summarized as follows:

1. In spite of the small N, areas of fast search could be made out for all 4 S's and 5 exposure times. They lay well within the stimulus matrix, due plainly to the small stimulus-difference employed. The contours seemed quite sharp, though sharpness is relative to the stimulus-spacing.

2. The shapes of the areas recalled the description given by Chaikin *et al.*: ovaloid, with the longer axis horizontal, and with many irregularities. Some of the irregularities might well have been due to the small N.

3. Two of the 4 S's gave an area that was nearly constant over the range of exposure-times, 6-80 millisec. One S gave a slightly *decreased* area with longer exposure times; the fourth S a markedly decreased area.

This is the opposite of a Roscoe-Bunson effect. Use of a tilt-discrimination seems to have achieved the desired independence of Roscoe-Bunson control, at least as far as exposure time is concerned. The decreased areas at longer times might have been due to some blurring of the lines. A narrower line might be better.

4. The exposures were brief and the stimulus difference relatively small; consequently a few erroneous responses occurred, in spite of the fact that these were conscientious S's. The highest proportion of erroneous responses made by any one S was 2.4%; two S's made almost no errors. The errors were of both kinds: positive responses to blank stimuli, and substantially erroneous localizations. They occurred almost entirely at the beginning of the experiment. The use of a longer practice period and a larger stimulus difference should reduce them nearly to zero.

What would a much better method look like? We can now offer some guesses about it, and itemize them as follows:

1. For most research purposes, we want a discriminable characteristic that is independent of Roscoe-Bunsen control. The inclination of short straight lines is a good candidate.

2. The difference between the critical stimulus and the background stimulus should be large; so large that a larger one would not significantly improve the discrimination. Accordingly, the stimulus field must be large, in order to contain the area of fast search.

3. For economy, the method might be a one-line, axial method. Economy will be necessary, in order to favor the many experiments that are already in sight.

4. For most purposes, a medium stimulus density is called for; a density low enough to fall into the density-independent range of areas, and high enough to delimit the area closely. This necessitates a prior experiment

that varies systematically the density of elements in a one-line matrix.

5. In order to find regularities, the focus of interest should be on fast search. Successive search is a highly variable process, and tachistoscopic exposure will largely eliminate it. There are severe problems of designing a suitable apparatus.

6. For the sake of objectivity, the method should most probably be a liminal method. A forced-choice method would provide even greater objectivity, if a proper one can be found.

7. The S's fixation should be monitored and thereby well controlled. Perhaps substantial slips in fixation could be picked up and signalled to E, so that certain poor observations could be discarded. It is conceivable that close control of fixation would produce a characteristic and invariant shape of the area of fast search, like a circle or square or rectangle, not yet found.

The foregoing list demonstrates that, in addition to economy and objectivity, we are seeking methodological independence. We want the area, as measured, to be independent of the particular intensity, exposure time, stimulus difference and stimulus density that are used. Independence of discriminable characteristic is equally desirable, but far more difficult to achieve.

Plainly this much better method is a long way off, but not as far as it was at the beginning of our research, when (in the language of the preceding report) we sought for "a method that might do justice to the process of search in a rich visual scene."

V. The effect of subdividing matrices on the speed of search.

Unlike the preceding problems, that sprang from other experiments, this one came from a practical situation. It is sometimes necessary to scan large, monotonously repetitive displays for low-probability targets. One might argue for subdividing the displays, on two grounds: first, to ensure that all of the display is searched at least once, and thereby to reduce errors of omission; secondly, to reduce redundancy of search, and thereby to raise its efficiency. If a matrix is undivided, parts of it must in effect be searched several times, to insure that no part has been omitted.

Our finding of the critical number, and of the area covered by it, suggests that subdivision should lead to faster search if the subdivisions are of an optimum size. If possible, each subdivision should contain about the critical number of elements at the given density of elements. When the subdivisions are much smaller than this, time will be wasted in searching small cells one by one. When they are much larger than the optimum, each sub-division must be searched unreliably and redundantly, like a large undivided matrix.

The obvious experimental plan calls for measuring the speed of search in a large undivided matrix, and repeating the measurements with subdivisions of various sizes. Miss Margaret Philbrick (Mrs. David B. Truman) prepared the elaborate stimulus material, ran the experiments and analyzed the data. In the first, somewhat tentative experiment, she subdivided a large square matrix of 3136 solid black circles (56 x 56) with thin black lines (see Fig. 15). In some exposures the subdivisions were square or approximately square; in others, they were rectangles having a width-to-height ratio of

Fig. 15

Showing (at bottom) a sample from a stimulus matrix divided by black lines; upper left corner of the matrix only. Also (at top) a sample from a stimulus matrix divided by white spaces; upper left corner only.

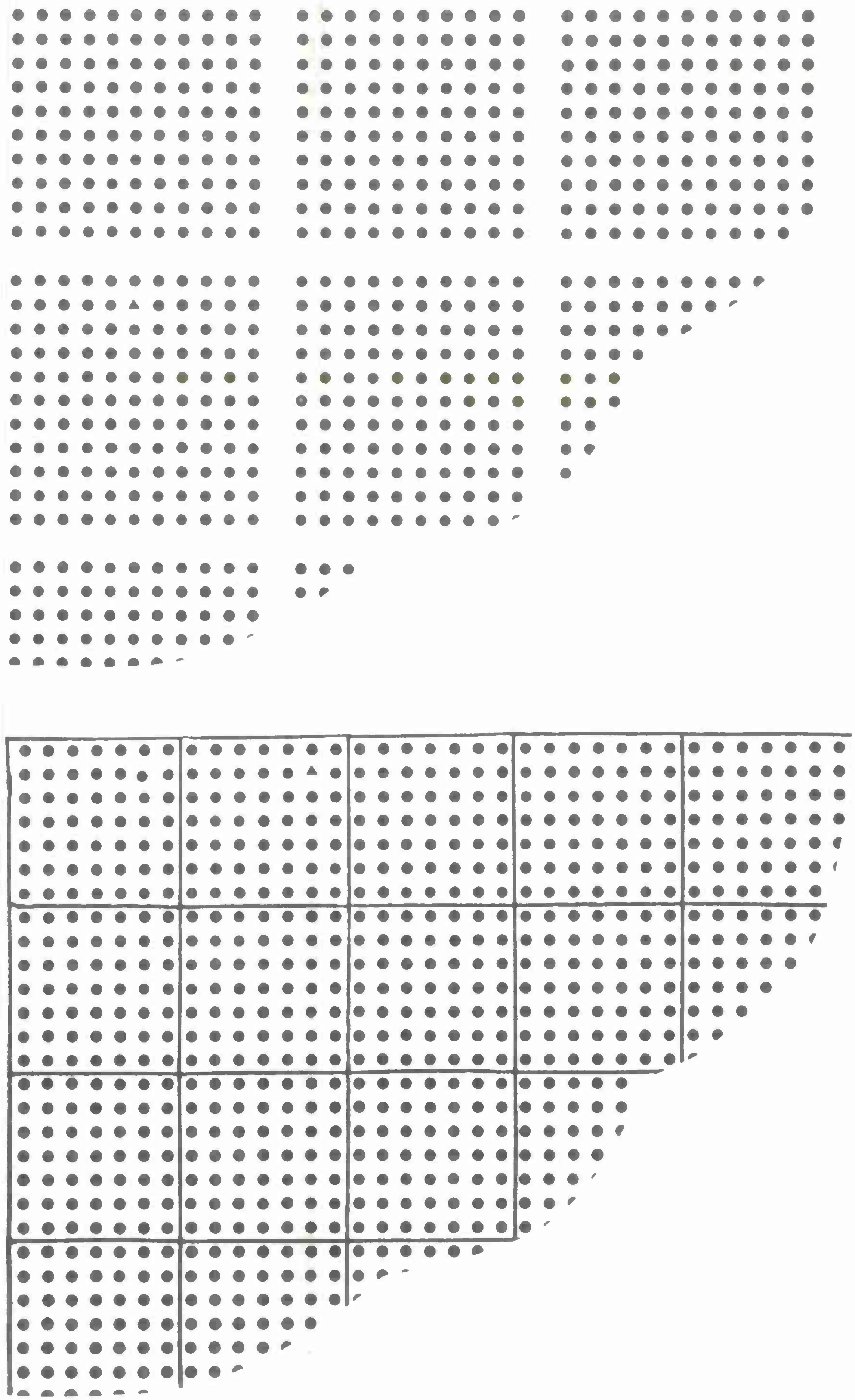


Fig. 15

about 2:1. The density of the matrix was constant and high; equal to the highest density used in the first experiment of this report, and the density used by Carter in the first experiments on critical number. The principal independent variable was the number of elements in the cell: a variable substantially confounded with stimulus area, since the internal density of the cells was constant.

The cellular subdivisions of the large matrix varied widely in the number of elements that they contained. For the rectangular cells, these numbers were exactly or approximately as follows: 8, 63*, 175*, 392. For the square cells, they were: 16, 64, 132*, 342*, 784. The starred numbers are approximate, because the actual cells had to be either slightly smaller or slightly larger than this in order to fit into the 56 x 56 matrix. The control case was provided by the undivided large matrix, which appeared in random order along with the subdivided matrices.

The critical element was the solid black triangle used so often in our experiments. There were 32 locations of this triangle, scattered over the undivided large matrix. When any grid was imposed on the matrix, the S could not predict in which cell the triangle might appear. One in 33 exposures had no triangle at all. The order of presentation provided complete randomization for cell-size, cell-shape (square or rectangular), and location of the triangle. Consequently, the S knew that the stimulus pattern would be square, of large area, and centered about the fixation mark. She did not know whether the grid would be coarse or fine; whether the cells in it would be square or rectangular; indeed, whether there would be any grid at all. She did not know where the triangle would be, or whether there would be any triangle at all. If there was a triangle, she knew that there would be only one. There were two S's, tested for vision with the Orthorater, and neither wore glasses. There were in all

330 stimulus sheets, and each S saw each sheet 5 times in 5 different random orders; this adds up to 1650 observations per S over the experiment as a whole, or 3300 in all.

The apparatus and viewing situation were the same as those described in the "improved method," pp. 18-22, of the preceding report, and used in the first three experiments of this report. The principal features were the opaque projector and screen, the large shutter, the fixation mark, the lasting exposure of the matrix field, the manual response, and the erasing field. The instructions were somewhat different, because the use of grids favored a systematic pattern of successive search. The S began by fixating in the center of the matrix, but the large area and high density of the matrix plainly compelled successive search in most exposures. The relevant portions of the instructions follow:

"Begin your search in the center of the screen. If you don't see the triangle immediately, search for it in the general way that you would use for reading. Begin at the top left and search to the right; quickly back to the left; then to the right again and so on.

"Note: you need not search dot by dot or cell by cell; the point is to find the triangle."

In other parts of the instructions, the grids were represented as a possible aid to search. From this point of view, the results were clear enough, but almost wholly negative. If we had no other evidence, we would conclude from them that subdividing a matrix does nothing but slow down the successive search of a matrix. Figs. 16 and 17 show for the two S's respectively the median latency of search as a function of the number of elements per cellular subdivision. (The area of the cell is substantially proportional to the number of elements in it.)

Fig. 16

Showing for subject PN, the median search time as a function of the number of elements per cell. The matrices were divided with black lines. The axes are semi-logarithmic. Some matrices had square cells and others rectangular cells, as indicated by the code. The horizontal dashed line indicates the median latency for the undivided matrix.

Fig. 16

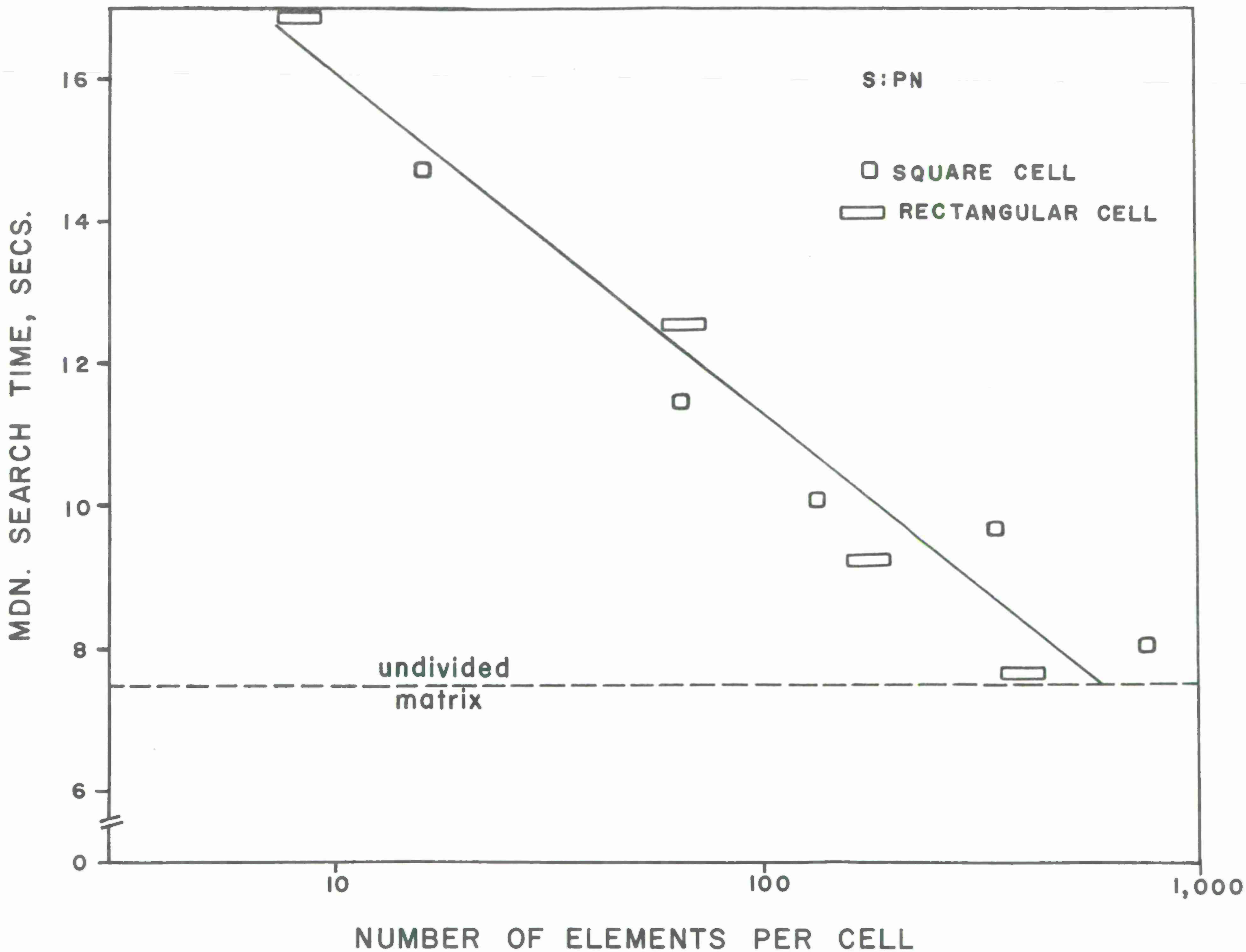
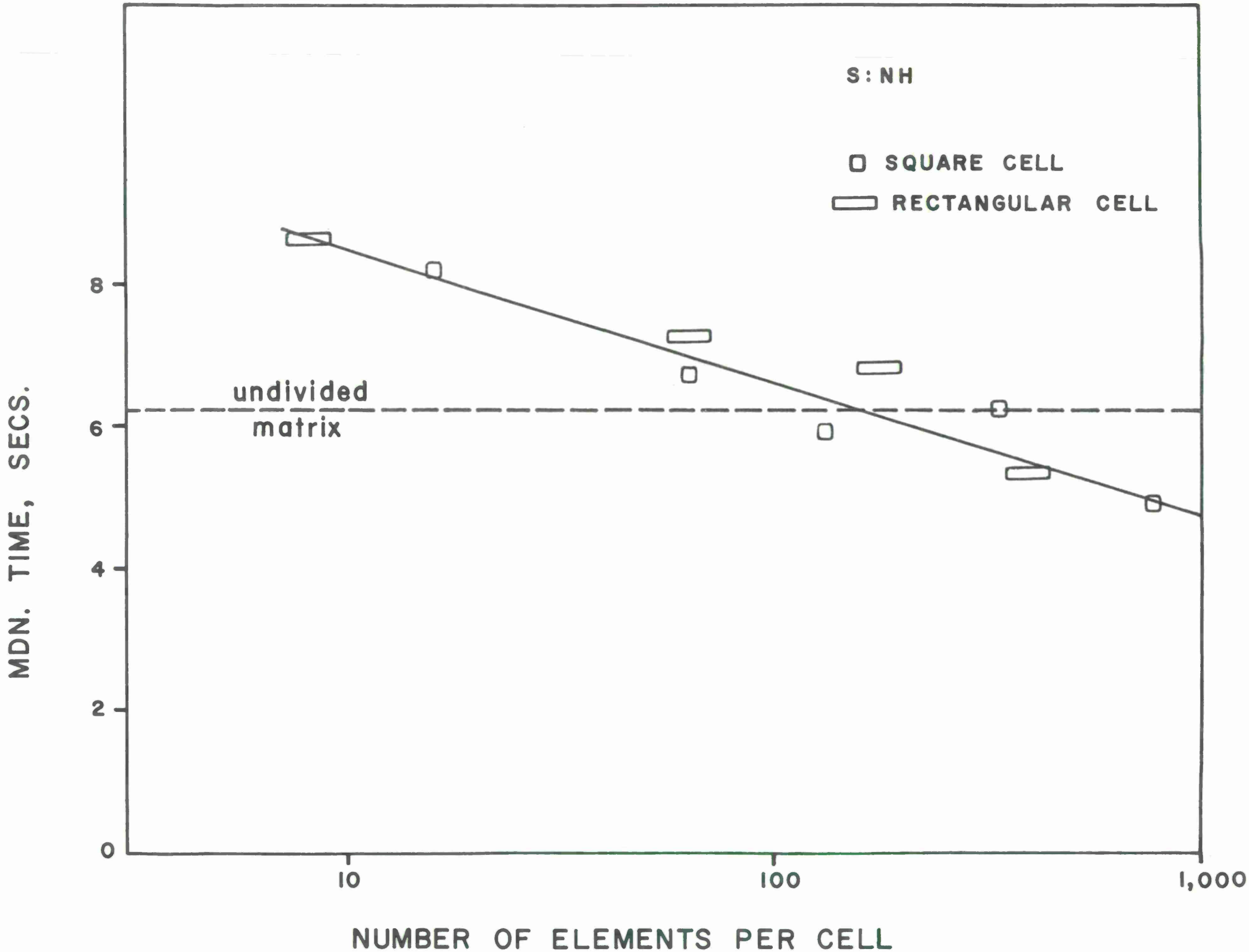

S:PN
SQUARE CELL
RECTANGULAR CELL
MDN. SEARCH TIME, SECS.
16
14
12
10
8
6
0
undivided
matrix
10
100
1,000
NUMBER OF ELEMENTS PER CELL

Fig. 17

Showing for subject NH the median search time as a function of the number of elements per cell. The matrices were divided with black lines. The axes are semi-logarithmic. Some matrices had square cells and then rectangular cells, as indicated by the code. The horizontal dashed line indicates the median latency for the undivided matrix.

Fig. 17


S:NH
SQUARE CELL
RECTANGULAR CELL
undivided
matrix
MDN. TIME, SECS.
8
6
4
2
0
10
100
1,000
NUMBER OF ELEMENTS PER CELL

Latency decreases with cell-size; the relation can be approximated with straight lines on the semi-logarithmic plots. For one S, PN, all of the subdivided matrices took longer to search, on the average, than did the undivided matrix. For NH, all but three subdivided matrices took longer. The datum points for square cells and those for rectangular cells fall into the same trend. The relation must be regarded as a very approximate one; as will be seen in the next experiment, these median latencies are subject to large variations. The latency for the control condition is also subject to a large variation.

The general trend of the results suggested a model that was extremely simple (but not very good). The model assumed that the matrix was searched one cell at a time; that each cell, regardless of its size, was searched in a constant short time (such as 0.4 sec., for example); that matrices containing a critical element must have been searched half way through before the element was found, on the average. The equation that these assumptions yield does not describe the data; its predicted times are too long for small cells and too short for large ones. Failure of the simple model reminds us of two features of the successive search performed under our conditions. First, the small cells were not searched one by one, but in groups. The instructions, quoted above, expressly permitted this. Secondly, the larger cells were too large (and too dense) to be covered by a single fast search. These are some of the complications with which a model-builder must cope.

The results fitted with only half of our original expectations: that when the cells contain fewer than the critical number of elements, time will be wasted in searching them. The possible advantage to be gained in having cells of an optimum size did not appear. This suggested that there might have been some unfavorable condition for the search of the subdivided matrices. We had already noticed something that might be unfavorable: the dividing line placed close to a row or column of elements on each side, produced a band of dark shading along its course. Both the line and the elements were solid black, and the matrix-density was high. Perhaps the shading tended to obscure the elements that lay in it, and slowed down the search.

With this possibility in mind, we designed the next experiment with a different mode of subdivision. A whole row or column of elements was removed to provide a white space as a means of subdivision. This took out the murky shading, although it also introduced some complications. We are not trying to establish white-spacing as a practical means of subdividing all material to be searched. Visual material already organized in matrices might indeed be successfully subdivided in this way, but the pulling-apart of continuous material (like an aerial photograph of a landscape) might break up exactly the feature which is being sought. Half a building might look like no building at all.

The experiment was much like the preceding, somewhat preliminary one. The original, undivided 56 x 56 matrix of solid circles in high density was the same. The critical element was still a triangle. The cells were still square or rectangular in shape. The independent variable in the experiment was the number of elements per cell, and the dependent variable was the median latency of search, taken over all locations of the critical element. The apparatus and viewing situation were the same. The S's initial fixation was central, as before. The instructions were much the same, except that they referred to white spaces as the mode of subdivision. The order of presentation was randomized as before over the variables of cell size, cell shape, and location of the critical element. So the S's uncertainties regarding the next exposure were substantially the same.

There were 28 locations of the triangle; these were fairly well scattered over the basic undivided matrix, except that the frequent occurrence of white spaces (i.e., of omitted rows) forced a paucity of locations between horizontal rows nos. 42 and 50. The cell sizes were as follows, in number or mean number of elements per cell; the approximate total number of elements in the matrix is given in parentheses. The rectangles: 21 (2058), 48* (2440), 153* (2754), 364* (2912); the squares: 49 (2401), 108* (2704), 324 (2916), 756* (3024). The total number of elements in the subdivided matrices is less than the 3136 of the undivided matrix, because rows and columns of elements have been stripped out to make the subdivisions. The asterisks denote approximate sizes; in order to fit into the large matrix as subdivided, the cells had to be either somewhat larger or somewhat smaller than this. Some smaller cell-sizes used in the preliminary experiment were omitted in this one.

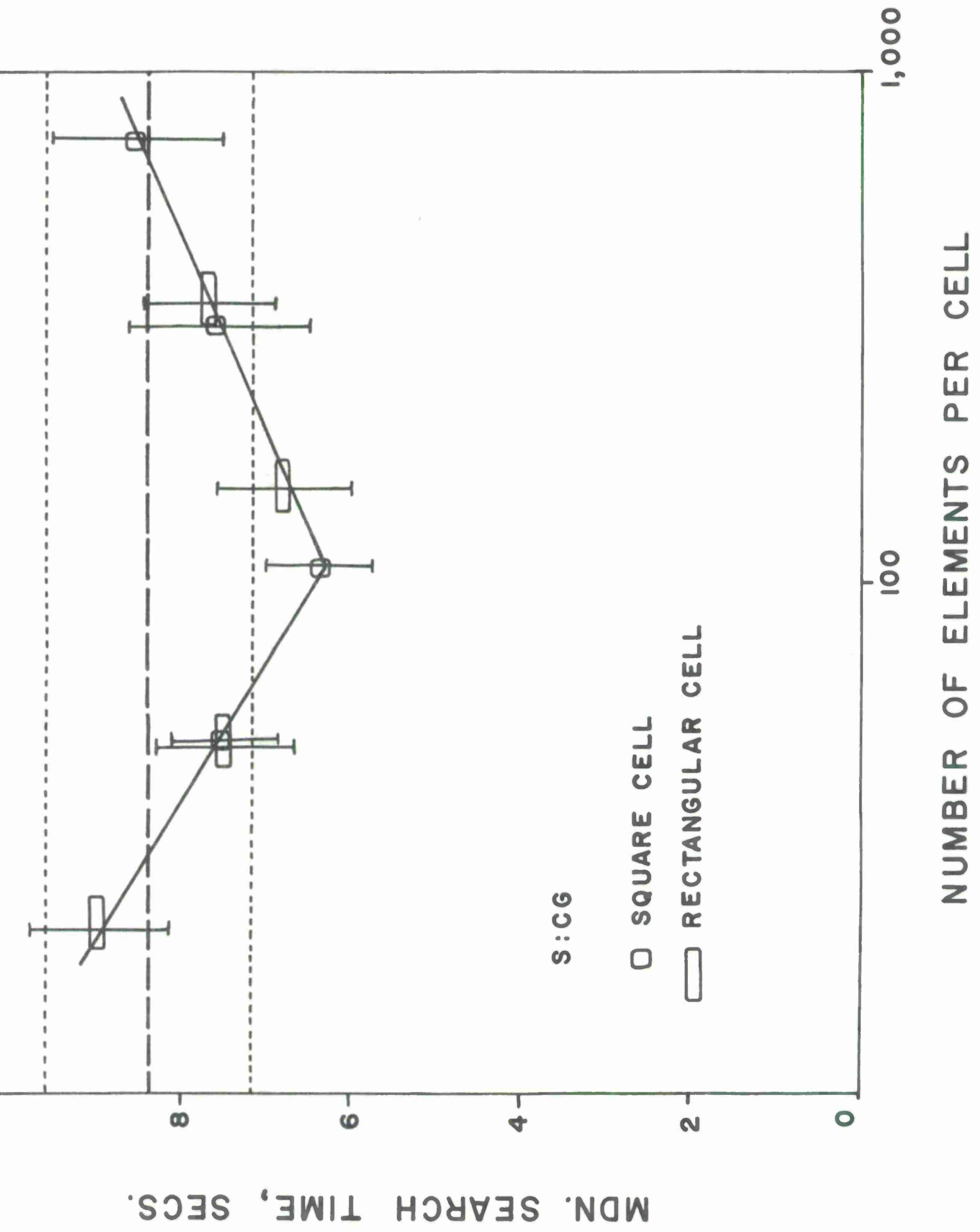
Four S's, screened for good vision, served in this experiment. There were 261 stimulus sheets. Each S saw each sheet as projected 5 times in 5 different random orders; the total number of observations in the experiment was 5220.

The results are very different from those of the preceding experiments. The method of subdivision is apparently important. Figs. 18-21 present the results for each of the 4 S's. First let us compare the median latencies for the subdivided matrices with the latency for the undivided matrix (the control condition), neglecting for the time being the standard errors of the medians. Over at least the middle portion of the range of cell-sizes, the medians for most of the subdivided matrices are less than the median for the undivided matrix. This might indicate an advantage for the subdivided matrices in speed of search.

Fig. 18

Showing for subject CG, the median search time as a function of the number of elements per cell. The matrices were divided with white spaces. The axes are semi-logarithmic. Some matrices had square cells and others rectangular cells, as indicated by the code. One standard error of the median is plotted above, and one below, each median point. The dashed horizontal line indicates the median latency for the undivided matrix; the dotted horizontal lines are drawn one standard error above, and one below, this median.

Fig. 18



S:CG
SQUARE CELL
RECTANGULAR CELL
MDN. SEARCH TIME, SECS.
0
2
4
6
8
100
1,000
NUMBER OF ELEMENTS PER CELL

Fig. 19

Showing for subject PN, the median search time as a function of the number of elements per cell. The matrices were divided with white spaces. The axes are semi-logarithmic. Some matrices had square cells and others rectangular cells, as indicated by the code. One standard error of the median is plotted above, and one below, each median point. The dashed horizontal line indicates the median latency for the undivided matrix; the dotted horizontal lines are drawn one standard error above, and one below, this median.

Fig. 19

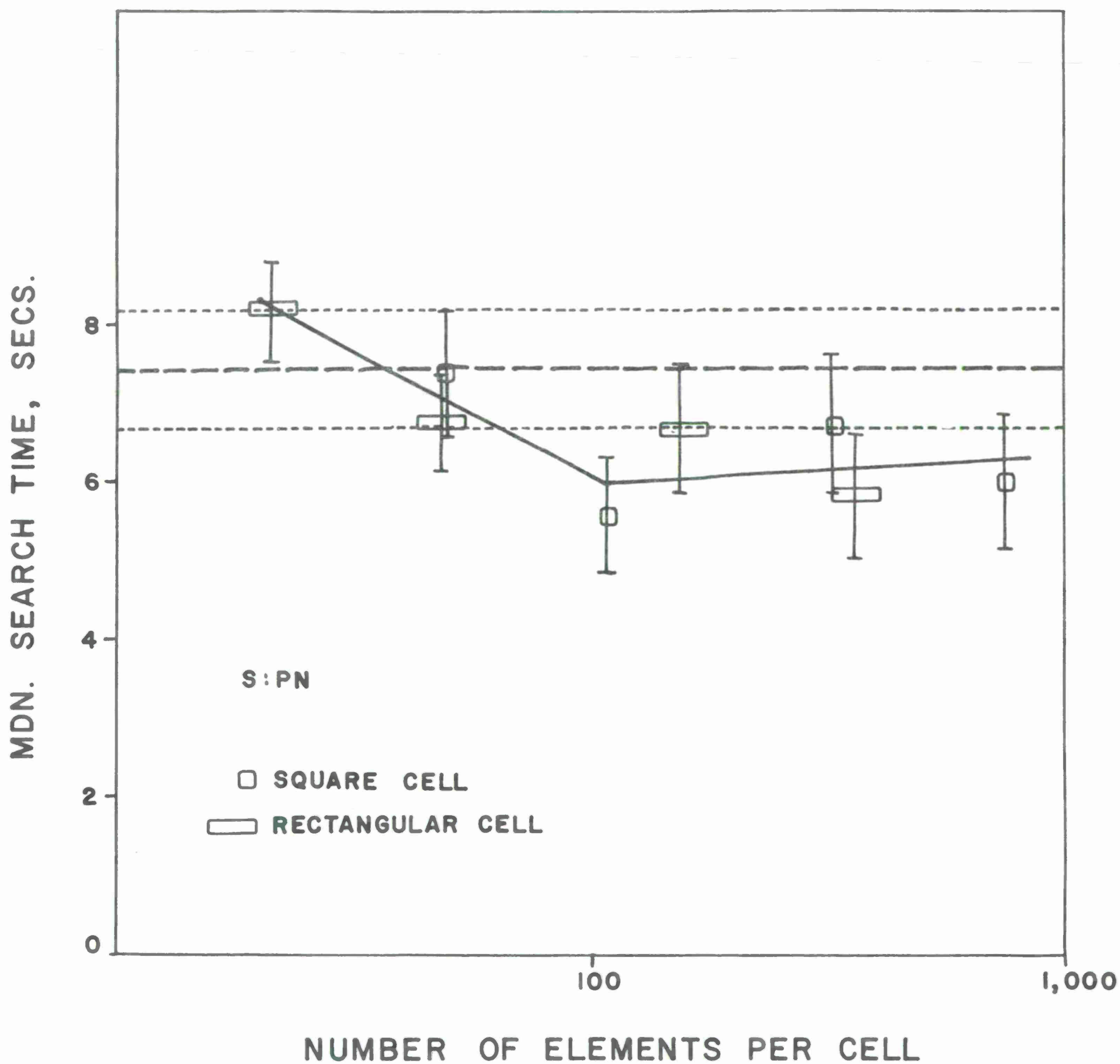

MDN. SEARCH TIME, SECS.
0
2
4
6
8
S:PN
SQUARE CELL
RECTANGULAR CELL
100
1,000
NUMBER OF ELEMENTS PER CELL

Fig. 20

Showing for subject NH, the median search time as a function of the number of elements per cell. The matrices were divided with white spaces. The axes are semi-logarithmic. Some matrices had square cells and others rectangular cells, as indicated by the code. One standard error of the median is plotted above, and one below, each median point. The dashed horizontal line indicates the median latency for the undivided matrix; the dotted horizontal lines are drawn one standard error above, and one below, this median.

Fig. 20

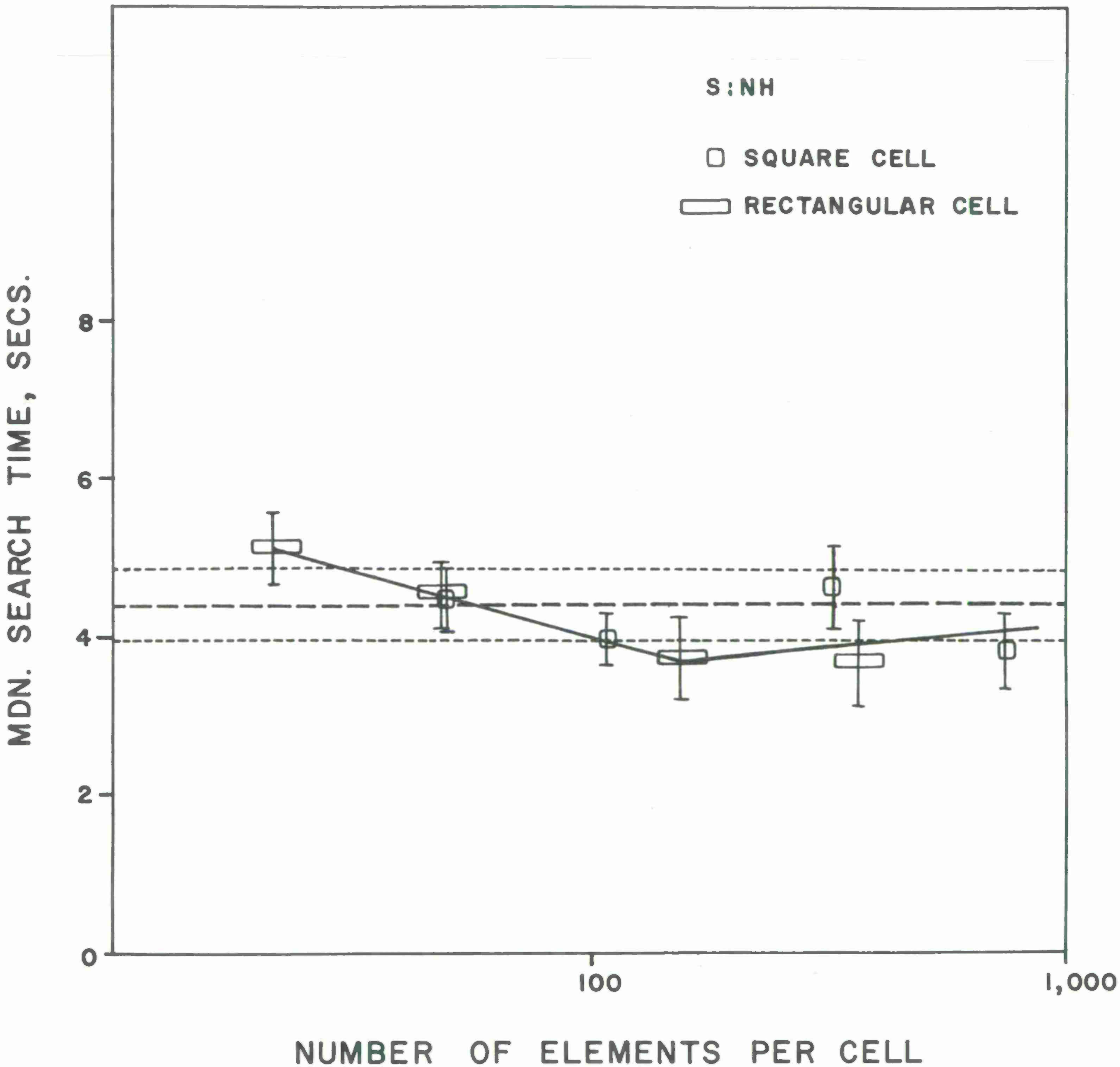
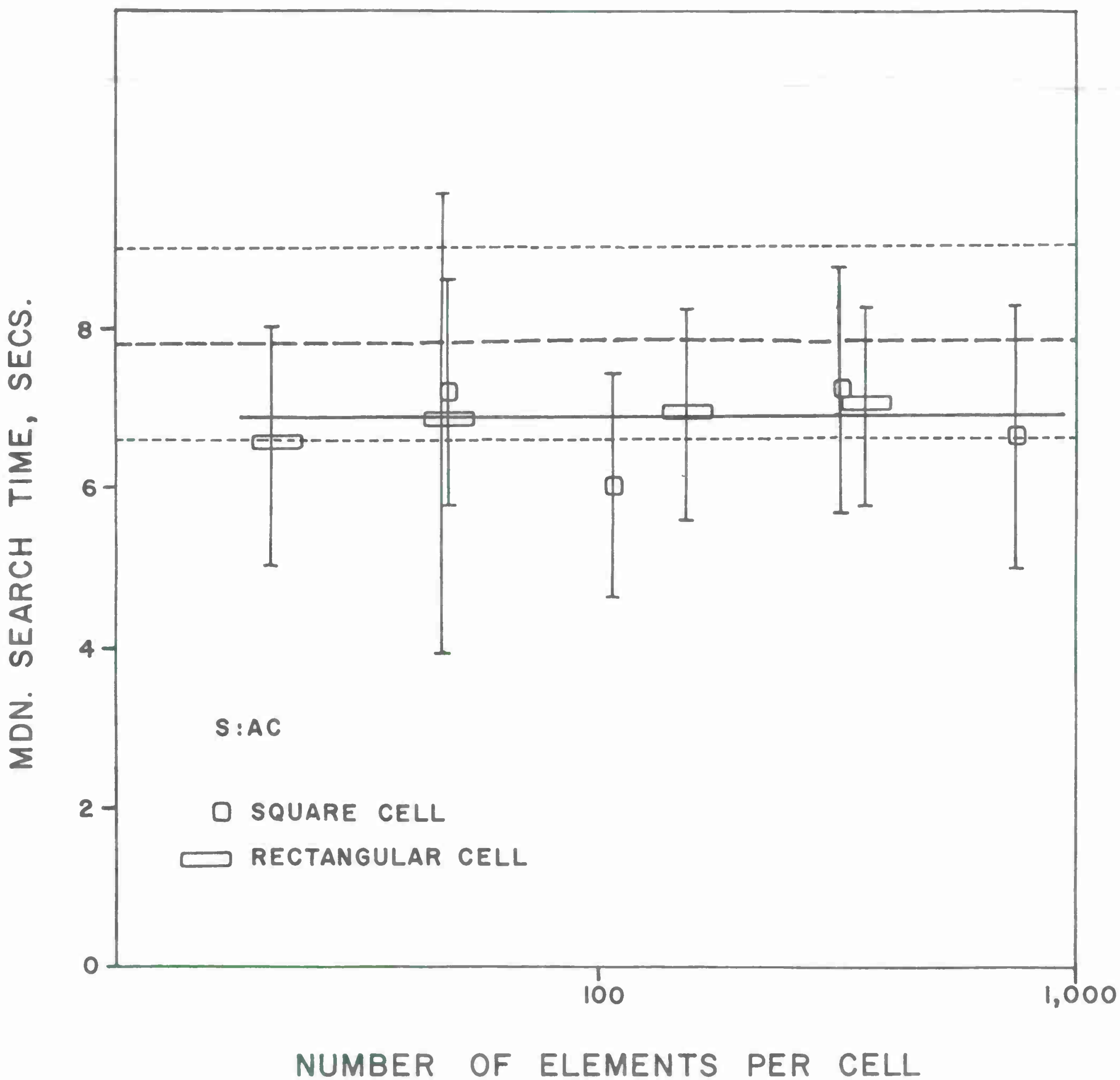

S:NH
SQUARE CELL
RECTANGULAR CELL
MDN. SEARCH TIME, SECS.
8
6
4
2
0
100
1,000
NUMBER OF ELEMENTS PER CELL

Fig. 21

Showing for subject AC, the median search time as a function of the number of elements per cell. The matrices were divided with white spaces. The axes are semi-logarithmic. Some matrices had square cells and others rectangular cells, as indicated by the code. One standard error of the median is plotted above, and one below, each median point. The dashed horizontal line indicates the median latency for the undivided matrix; the dotted horizontal lines are drawn one standard error above, and one below, this median.

Fig. 21


MDN. SEARCH TIME, SECS.
0
2
4
6
8
S:AC
SQUARE CELL
RECTANGULAR CELL
100
1,000
NUMBER OF ELEMENTS PER CELL

Nevertheless, three complications appear. First, the indicated advantage is small, only 11% - 24% at the maximum. Secondly, the standard errors of all the medians, including the medians for the undivided matrix, are quite large. (This complication calls for an improvement in method, and is discussed below). Thirdly, the total number of elements in the subdivided matrices is less than the number in the undivided matrix, as noted above. Perhaps the apparent advantage of sub-division is due to this. In view of all three complications, no further statistical treatment is justified, and we cannot safely infer the advantage of the subdivided matrices in speed of search.

The graphs offer something besides a comparison of subdivided and undivided matrices; they suggest an interesting relation between the size of subdivision and the speed of search. Our original hypothesis predicted that latency would be at a minimum when the number of elements in the cells equalled the critical number for the given conditions of search. Fig. 18 shows exactly such a minimum for S:CG. Figs. 19 and 20, for PN and NH, are somewhat less clear, and AC shows no minimum (Fig. 21). The preliminary experiment gave clear evidence of a descending branch in the relation that we are considering; the evidence for the ascending branch comes only from Figs. 18, 19, and 20.

The <u>location</u> of the presumed minimum, as drawn in Figs. 18-20, is just what the original hypothesis would predict. Carter's first experiments, described in the preceding report, used the same elements, the same density and the same general viewing situation. The critical numbers for her S's ranged between 80 and 180 elements. The minima for CG, PN and NH in the present experiment are 110, 110, and 150 respectively.

What are the practical implications of this experiment? They are largely negative: on this evidence, we cannot recommend the subdividing of matrix-material or continuous material in the interest of speeding up the search. If subdivisions are used, it should presumably be to ensure the reliability of search: to make certain that no targets are missed. In this case, the subdivisions should be relatively small; smaller than the area of fast search is likely to be, even in dense material. Small subdivisions, searched one by one, should favor reliability at some expense of speed. As an added practical point: the means of subdivision is worth some study and trial, in order not to slow search unnecessarily, or to conceal some targets.

Finally, we can ask what a better method might be for studying successive search. Obviously the methods used in our experiments left something to be desired. The suggested method draws its inspiration from psychometrics: specifically, from crossout tests of clerical aptitude. In these tests, the S scans lines of randomized printed letters and crosses out all of the *e*'s, for example.

The elaborate apparatus that we have used is largely unnecessary for studying successive search. At the same time, the viewing situation should be controlled in ways that are not found in psychometric practice. The viewing distance, the viewing angle and the illumination should all be controlled, for example. The matrices would be produced on paper, and exposed behind glass or clear plastic. So far, the description of method follows ordinary laboratory practice.

The general pattern of scanning would be controlled by instruction, although the specific path would not always be so controlled. S would fixate in the upper left corner of the aperture, and would use the left-to-right, sawtooth scan of reading English. On finding a critical element, he would point to it on the glass; the time of the pointing would be recorded automatically to 0.1 sec.; E would monitor the accuracy of the pointing. The stimulus sheets and the total matrix area would be relatively large; the aperture might be 1 ft. square, placed at reading distance. There could be more than one critical element per sheet, but the number would be small, say 0-3. S would search to the end of the sheet in any case.

The use of white-spacing makes it impossible to hold constant both the total area of a subdivided matrix and the total number of elements in the matrix. In studying successive search, it is most probably more important to hold constant the total number of elements than the total area of the matrix.

A better method of subdividing than either black lines or white-spacing must be found. Black lines on paper are not good with high-density matrices, and white-spacing will not work at all with low-density matrices. Both methods are most probably poor for use with continuous material (as opposed to matrix material). One obvious possibility is to scribe the grid on a plastic overlay, and to color the lines; edge-illumination might assist. On the other hand, it is not easy to ensure the registration of an overlay with densely-spaced material on a stimulus sheet. Perhaps there are no easy answers in this field.

Both speed and accuracy should be studied as dependent variables. The S should work in some sessions under an accuracy-instruction and in others under a speed-instruction. For most practical applications, accuracy is more important than speed.

When the general pattern of search is controlled, it should be possible to obtain better measures of speed than the ones yielded by our two experiments. In those experiments, a single cell-size gave very variable latencies simply because some critical elements lay near the top of the divided matrix, and others near the bottom. (The S had been instructed to work from top to bottom in the usual case, as described above). The large standard errors reflect this source of unnecessary variation. To reduce the variation, one could try the following scheme: in the analysis of latencies, divide the whole matrix into tenths, top to bottom, irrespective of the actual subdivision of the matrix. Group together the latencies for those critical elements that lie in a given tenth. Plot the median for the group against the tenth from which it is derived. The graph should be nearly linear, and should pass through the origin. If so, its slope would measure the speed of search for a given S and experimental condition. The slope could be readily determined by the method of averages.

When successive search is placed under some experimental restrictions, psychologists should not only obtain more regular data but more comprehensible data. The psychological model-builder would then have a fair chance. To assist him, we can call attention to the concept of the area of fast search, developed in this report and the preceding one; also to the complicated relation between the area of fast search and the density of the matrix.

VI Conclusions

1. The critical number varies widely with stimulus density. It increases over the entire range of densities used in our experiments. (The critical number and the basal time, referred to below, are defined in the text.)

2. The stimulus area occupied by the critical number is constant over a range of lower densities. This finding is supported by a second experiment with an independent graphical method, although the method is very insensitive. Under our conditions, this constant area of fast search occupies a visual angle of about 10 degrees.

3. Over a range of higher densities, the area corresponding to the critical number shrinks, but the critical number itself continues to increase.

4. The basal time is constant as a function of stimulus density, over the whole range of densities employed.

5. The results offer more evidence that the <u>shape</u> of the area of fast search is ovaloid, with the long axis horizontal. (The viewing is binocular.) It now appears unlikely that the shape is determined either by the shape of the stimulus array or by the S's uncertainty regarding the location of the critical element.

6. Successive search yields long and variable latencies, as would be expected. There is some evidence for patterns of successive search that are characteristic of the individual S.

7. In successive search, high-density matrices require more time than low-density ones.

8. The expansion of the area of fast search with increasing exposure time, previously reported by our project, is most probably due to control of a form-discrimination by the Roscoe-Bunsen Law. Preliminary evidence

indicates that the use of a different discrimination (visual inclination) does not produce an expanding area.

9. We may envisage an improved method of studying fast search, that seeks independence of exposure-time, intensity, stimulus-difference and stimulus-density. It also seeks objectivity and economy. The method is not yet in hand.

10. Subdividing a matrix has no demonstrated advantage in speeding up the search of the matrix. If subdivision is used, it will presumably be to increase the reliability of search.

11. There is some evidence that the speed of searching a subdivided matrix is maximal when each cell in the matrix contains about the critical number of elements.

12. The method of subdividing a matrix is important. An inappropriate method may reduce the speed of search considerably; presumably it could also affect the reliability of search.

13. We may envisage an improved method of studying the successive search of divided or undivided stimulus material. The method would impose a controlled pattern of search. It might provide more reliable measures of the speed of search, and an opportunity for the psychological model-builder.

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13. ABSTRACT

This report describes six experiments on visual search, in continuation of those described in the report ESD-TDR-64-535, entitled The Range of Visual Search. Two essential terms in the report are critical number and basal time, defined by the following operations. Median latency of search is plotted as a function of the number of elements in the matrix, for each subject and experimental condition. At low numbers of elements the latency is nearly constant; this is the basal time. Then there occurs a transition to longer latencies. The critical number is the number of elements at which the transition occurs. The aim of the first experiment was to discover whether the critical number varies with the density of the stimulus matrix. It certainly does, over the entire range of densities employed. Nevertheless, the area corresponding to the critical number is apparently constant over a range of low densities. (This is the area of fast search.) Over a range of high densities, this area decreases considerably. Basal time does not vary with density. The second experiment aimed to check the first one, and to provide evidence on the shape of the area of fast search. The analysis was in terms of the location of the critical elements in the matrix. The constancy of area at low densities was confirmed, although the check was very insensitive. Basal time is indeed constant. The shape of the area appears to be as previously described: ovaloid, with the longer axis horizontal.

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The third experiment aimed to try out a more economical method for mapping out the area of fast search. It used a single line of elements, titled at various angles. The method is promising, although further work on it is required. There is evidence for patterns of successive search that are characteristic of individual human subjects. The fourth experiment used the method of brief exposures, specially developed apparatus, and a different discrimination (the tilt of line-segments about the vertical). The preceding report had described the expansion of the area of fast search with increasing exposure time, and had related this expansion to the Roscoe-Bunsen Law. The results confirm this interpretation, although the number of observations is very small. The fifth and sixth experiments dealt with the subdivision of matrices. Does subdividing speed up successive search? One cannot yet conclude that it does; if subdivisions are used, it will presumably be to ensure the reliability of search, at some expense of speed. The method of subdividing is important. There is evidence that speed of successive search is maximal when the number of elements in each cell of the matrix is about equal to the critical number. The report makes specific suggestions about improved methods for studying both fast search and successive search.

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